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PRINCIPLES OF PALEONTOLOGIC CORRELATION.[1]

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General discussion.—Geologic correlation has been carried on ever since the pupils of Werner endeavored to recognize his stratigraphic divisions in remote parts of the earth; and since William Smith discovered that fossils are characteristic of certain formations, paleontologic correlation has been attempted. Still it must not be forgotten that the greater part of the correlation that has been done up to this time is based on lithologic and stratigraphic rather than on faunal data. Fossils have been regarded as incidental, useful in recognizing strata, but not as a basis for subdivisions on account of changes in fauna or flora.

Where a rock-bed of distinctive character is persistent over a wide extent of country, a lithologic correlation would reach as good, and often even better, results than could be obtained from

[1] Read before Section E. Amer. Assoc. Adv. Sci., June 28, 1900.

paleontologic data. But outcrops of strata are deceptive, and often apparently continuous beds of the same character turn out to contain a number of different formations. In the western states such lithologic and stratigraphic correlations have been, more often than not, erroneous, while in the Mississippi valley region they have usually been at least approximately correct, because the great geologic events that were the causes of the stratigraphic changes were uniform over wide areas. Even today the catastrophe doctrine of Cuvier makes itself felt, and we find paleontologists and stratigraphers using unconformities as a basis for the separation of Cretaceous from Jurassic, where the fossils do not tell a definite story, as if the uplift and erosion would necessarily come at the same time in Europe and America.

Paleontologic correlation itself is not infallible; it must be used intelligently, its sources of error known and guarded against, or else it is little more reliable than the lithologic method; these errors lie chiefly in defective knowledge of the vertical and horizontal range of species or genera chosen as criteria, and in erroneous identification of these forms. Careful collecting, accurate field and laboratory discrimination, and wide knowledge of the literature are the best safeguards.

Two sorts of paleontologic correlation may be recognized, the direct, and the indirect method. In a limited province, such as existed in England and France during Cretaceous time, faunas were distributed uniformly over the area and had the same range in the two countries. Thus correlation of English and French Cretaceous strata is simple and direct, for they represent sediments that were once continuous, that were laid down in the same basins or along the same margins, under the same climatic conditions, and contained the remains of a similar fauna.

On a larger scale the problem of correlating the western European Cretaceous beds with those of the Atlantic slope Cretaceous of North America is the same. These strata were all deposited in the same faunal region, and although there are provincial differences the American and the western European faunas are remarkably similar, with even many species in common to

the two provinces, and most of the genera. During Cretaceous time there must have been easy intercommunication between Europe and America by a submerged continental shelf, keeping well within the temperate conditions. This state of things persisted through the Eocene, for the same similarity of faunas has been noted on the two continents in strata of that period.

On a still larger scale the same sort of correlation has been carried out between the western American and the Alpine Upper Trias, where many of the species and nearly all the genera are common to the two localities, although they are not in the same province, nor even in the same faunal region, and separated by six thousand miles in a direct line, and by at least twelve thousand miles by the nearest direction in which migration could have taken place. Yet there must have been easy intercommunication by continental margins from the American region, through the Oriental, to the Mediterranean region, along the borders of the ancient Mesozoic "Tethys" or central Mediterranean sea, that stretched eastward from the Alpine province through Asia Minor, India, and at least to the borders of China and Japan.

Direct correlation is possible even where there is no community of species, if a number of characteristic short-lived genera be common to the two regions. Thus the student of stratigraphic paleontology has no difficulty in correlating the *Meekoceras* beds of the Lower Trias, whether they occur in the Himalayas, Siberia, California, or Idaho; the fauna is essentially similar in all these regions, although species common to them are not yet identified. These faunas must have had a common origin either in one of these regions or in some unknown outside region, and reached the American and Asiatic provinces by migration. The place of origin may have been distant enough for the migrant faunas to have become specifically differentiated by the time they had reached their distant goals. In fact this is probably by far the more common case. Absolute specific identity between regions as distant as Asia and America must be rare; in reality there are usually in common to such regions only what

are called "representative species." This is especially true in a time of quiet development, where the fauna is largely endemic, and where there was no chance for outside elements to get into the region.

Indirect correlation also may be of two kinds; the first of these is where no fossils of extra-regional distribution are known in a formation, but where the formations above and below can be recognized. An example of this is the classification of the Algonkian system or its equivalents; the clastic pre-Cambrian, and post-Archean sediments all over the world are placed in this division, although no fauna that is characteristic is known in them as yet. Such correlation can only be tentative or preliminary, as is the present classification of the Newark formation of the Atlantic coast.

The second sort of indirect correlation is where no fossils are common to two separated regions, but elements of both are found together in a third region. A good example of this is the correlation of the Cretaceous strata of the west coast of North America with those of the interior and the Atlantic region. During the greater part of Cretaceous time the two regions were separated by a land mass so that their faunas were totally distinct, not only the species but even the genera being different. And these difficulties are seen in the attempts of the earlier stratigraphers to assign the various formations to their proper places. But when the Indian Cretaceous fauna was described, it was seen at once that there were striking analogies between that and genera and species of California. And since the Indian formation was accurately correlated with the Cretaceous of Europe, it became comparatively easy to assign the Californian strata to their proper place by this indirect comparison with the European standard. The Cretaceous of the Atlantic region had long before this been correlated with European, and thus the formations of the Atlantic region and of the Pacific coast were finally placed in harmony through the medium of comparison with a region thousands of miles from either.

Paleontologic zones. — Ever since William Smith demonstrated

that the various beds of the English Jurassic may be recognized by their fossils, the stratigraphy and paleontology of this formation have been a favorite field for investigation. Jurassic strata with abundant marine fossils are widely distributed in England, France, Germany, and Switzerland, in easy reach of universities and museums, so that the student of these faunas has an unusual wealth of material at hand. And in this western European province comparatively uniform conditions prevailed during the greater part of this time, allowing the faunas to become widely distributed. It is doubtful if any other succession of fossil faunas in the world is so well known as that of the Jurassic of this province, or if anywhere else such minute stratigraphic and faunal division has been successfully carried out; for there is not a single bed in all the great thickness of Jurassic sediments that does not contain somewhere in this province a rich marine fauna.

Quenstedt devoted his life to a minute subdivision of the Jurassic of Württemberg, establishing a classification that still holds sway in Germany; but this classification was based on local faunas, whose appearance and disappearance were caused by insignificant local changes in sedimentation, and it could hardly be used away from the place where it originated. In this scheme the greater unconformities, overlaps, and faunal changes received no more attention than the smaller geologic events. It was, then, merely a useful local classification, although of great value as a starting point in comparative study.

It was reserved for Albert Oppel,[1] a pupil of Quenstedt, to establish a chronological classification, based entirely on paleontology, and independent of lithologic development. For the entire Jurassic formation Oppel recognized thirty-three zones, or subdivisions characterized by certain species that occurred only in these horizons. The species chosen were of the greatest horizontal and the least vertical distribution, and were usually ammonites. These zones were thought by Oppel to be universal, for he was able to recognize them in Germany, Switzerland,

[1] Die Jura Formation, 1856.

France, and England, and by means of them was able to bring into harmony the local subdivisions already established in these various countries.

This was an important step in the right direction, but experience has shown, since Oppel's time, that these zones were not universal, and could seldom be recognized outside of the province where they were established — not even there always, when there was much difference of facies. So this scheme failed of its immediate purpose, although the final results of it have been more important than Oppel probably ever anticipated.

A further application and enlargement of Oppel's plan has been attempted by Buckman,[1] who has divided the Jurassic formation into *hemerae*, based on the occurrence of certain characteristic species of ammonites. An *hemera* represents a time considerably shorter than a zone, for the Lias, or Lower Jura, alone is divided into twenty-six *hemerae*. These are undoubtedly of much use to the stratigraphic paleontologist in England, probably in France, and possibly in Germany; but these *hemerae* can not possibly be identified away from the limited province where they were established, for in the Alpine or the Austrian Jura one is often lucky to be able to tell whether certain beds belong to Lower, Middle, or Upper Jura. Such finely drawn subdivision is of use only in local stratigraphy.

Buckman further classed a number of *hemerae* together in *ages*, based on the development of a group or series of species; in the Lias alone there are four of these *ages*, which correspond more nearly to the zones of Oppel, but even these could hardly be recognized in southern Europe, and much less in Asia or America.

Oppel thought that his zones were universal, or interregional, but only occasionally can one of them be identified outside of the province where it was named. This is due to the distribution of certain characteristic fossils outside of their usual range, on account of conditions temporarily facilitating interregional

[1] Quart. Jour. Geol. Soc. London. Vol. LIV, 1898. On the Grouping of some Divisions of so-called Jurassic Time.

migrations, which can occur only at times of readjustment of faunal provinces. There can be none in the intermediate periods of stability and quiescence when the fauna is endemic.

The writer proposes to retain the term "zone," in the sense intended by Oppel, as a chronologic term for a limited horizon, or time division, characterized by an interregional fauna. Use of the term in this significance would recognize not only biologic development, but also geologic events, for an interregional fauna can appear only in times of readjustment of biologic regions, of trangressions of the sea on the land, or of opening up connections between regions that before were separated. These are nature's periodic trial balances, during which the geologic columns in various regions, for a while divergent in biologic development and thus in stratigraphic classification, are brought into harmony.

A zone, in this sense, means a comparatively short time in which a certain characteristic, limited group of animals or plants lived—too short for any great faunal change, but long enough for this group to diffuse itself over a great area. To illustrate this let us take a well known example. It must have taken a long time for *Productus semireticulatus* to be dispersed through the seas of Australia, Eurasia, and America, for it is found in all those regions. But no stratigrapher would choose this species as a zone fossil, since it ranges from the Mountain Limestone into the Permian; often characteristic of a certain province during a given time, but of no one horizon everywhere. And during this long time the greater part of the accompanying faunas underwent enormous changes, until most of the genera, even, were new. During all these migrations *Productus semireticulatus* itself underwent modifications until it might be divided into a number of geographic species or varieties, and each of these into mutations or varieties in an upward-ranging genetic series. But accompanying *Productus semireticulatus* there are many species and genera that were short-lived and widely distributed, in some one region appearing as a link in a genetic series, but in some other region appearing sporadically or unheralded by local ancestors, and brought in by immigration

from the outside world. The appearance of such genera or species is an interregional event, and marks an episode in the dynamic history of the earth. Zones are thus not a figment of the stratigrapher's imagination, but are based on geologic events of far-reaching importance, in comparison with which the local shiftings of lithologic facies are insignificant.

Ancient faunal geography.—One of the first things that attracted the attention of naturalists engaged in the study of geographic zoölogy was that animals are not now distributed strictly according to climate, or other physical conditions. Edward Forbes early reached the conclusion that the ancient marine faunal provinces and regions by no means corresponded with the present distribution, and that the present faunal relations could be explained only by study of past geologic changes in the distribution of land and water. The various marine provinces were grouped by S. P. Woodward[1] in great regions: "The tropical and subtropical provinces might naturally be grouped in three principal divisions, viz., the Atlantic, the Indo-Pacific, and the West-American—divisions which are bounded by meridians of longitude, not parallels of latitude. The Arctic province is comparatively small and exceptional; and the three most southern faunas of America, Africa, and Australia differ extremly, but not on account of climate."

What is true of faunal geography today was true of it in the past. While certain faunas, such as the Silurian, have been very widely distributed, on account of the existence then of wide expanses of shallow marginal and epicontinental seas, there were no such things as universal faunas, even in the most remote geologic time. There have always been barriers of continent and ocean, and probably too of climate, ever since life existed on the earth. Only the deep sea faunas could be universal if oceanic basins had been stable; but such faunas are not universal now, nor have they remained unchanged in time.

Many years ago Barrande[2] showed that the Cambrian

[1] Manual of the Mollusca, 1856, p. 353.

[2] Système Silurien du Centre de la Bohême.

deposits known at that time could be grouped in well-defined geographic provinces; it is true that there was a great similarity of animal life in the various regions, but this by no means amounted to identity. Most genera had a wider range then than in later formations, but community of species was as rare in the Cambrian as in the later Mesozoic. Walcott has divided the Cambrian into three great divisions, each named after the most characteristic genus in it: the lower, or *Olenellus* zone; the middle, or *Paradoxides* zone; and the upper, or *Olenus* zone. No one of these had a universal fauna, although certain subdivisions can be traced through several provinces and even regions, and thus deserve the designation "zone," as Oppel used the word. It is noteworthy, too, that these times of interregional distribution come at periods of transgression of the seas on the land, so that a connection between these two phenomena may justly be inferred.

The work of Barrande, James Hall, and Murchison has shown that the Silurian strata and their fossils are as widely distributed as the Cambrian. But during Lower Silurian time the faunas of the American and the European region seem to have been largely endemic. The Trenton sea probably covered the greater part of North America, but only that in the northeastern part of the region shows much relationship to the European. During the Upper Silurian there was considerable readjustment and shrinkage of the sea, and as a consequence of this the Niagara limestone may justly be considered as an interregional zone, although the exact period of the migration cannot be determined.

During the Lower and Middle Devonian the division into regions that had existed in the Silurian still held sway, for it has been shown by H. S. Williams that there was a North-South American and a Eurasian region. But with the beginning of the Upper Devonian the connections had changed so that the grouping was Eurasian-North American, and South American-South African. This change shows itself in North America at the base of the Upper Devonian, where with the *Cuboides* zone

of the Tully limestone there was ushered in a fauna that could not possibly have been developed out of its local predecessors in the Hamilton beds, but whose affinities are with the Upper Devonian of Europe and Asia; in this latter region the *Cuboides* fauna is genetically connected with its predecessors of the Lower and Middle Devonian. In this invasion of the American waters by the *Cuboides* fauna, we have an undoubted zone, the first great interregional migration that can be traced in the history of the earth. But, as has been shown by Professor Williams,[1] this means something more than a mere migration, it means a complete readjustment of the faunal geography of the time. The invasion thus begun was kept up during the succeeding *Intumescens* zone, when Eurasian cephalopods began to make their way from the northwest into the New York[2] province. In these two zones we have divisions that are stratigraphically as well as faunally homotaxial with European beds, that is, they are virtually contemporaneous with them.

The Lower Carboniferous is well known to have beeen a time of extensive encroachment of the sea on the land, in Europe and America, but the boundaries of the sea were not uniform during the various stages of this age.[3] Oscillations within the regions were common, and sometimes they were great enough to allow the influx of an exotic fauna, such as those of the Kinderhook horizon, and of the St. Louis division. On a smaller scale the inter-provincial migrations, or colonies, are known at several different horizons of the Lower Carboniferous, occurring always at a time of expansion of the sea, as in the Burlington division of the Osage, and the St. Louis beds.[4]

The Upper Carboniferous, on the other hand, in the Mississippi valley region of the United States, and in western Europe

[1] The Cuboides Zone and its Fauna, Bull. Geol. Soc. Amer. Vol. I, 1890.

[2] J. M. CLARKE: Naples Fauna, Sixteenth Ann. Rep. New York State Geol., 1898.

[3] S. WELLER: JOUR. GEOL., Vol. VI, 1898, Classification of the Mississippian Series.

[4] H. S. WILLIAMS: Amer. Jour. Sci., Vol. XLIV, 1895, On the Recurrence of Devonian Fossils in Strata of Carboniferous age.

was a time of encroachment of the land on the sea, and only occasionally, when the sea had temporarily reclaimed its own, are marine faunas found in this formation. But when these occur, they are often extra-provincial, and occasionally extra-regional in origin, and thus give a secure basis for correlation with those regions where marine conditions still prevailed. Such a state of affairs existed in western North America and in eastern Europe during the time of the Coal Measures; in these regions the sea transgressed over the land areas, and allowed the marine faunas to become widely distributed. By intermittent subsidence of the low-lying coal swamps an intercalation of marine with freshwater deposits took place, allowing accurate correlation between the two facies.[1] And occasionally these oscillations have been something more than local events, for they have brought in exotic faunas, as in the case of the belated immigration of *Pronorites cyclolobus* and *Conocardium aliforme* in the Lower Coal Measures of America, or the appearance of *Gastrioceras* and *Paralegoceras* in the European waters long after they had appeared in America. The greatest of these disturbances was the Appalachian revolution, which at the beginning of Permian time raised finally above water the continental borders of the old Appalachian land mass, and left only a comparatively small basin for the Permian sea. This rising of the Mississippi valley region was undoubtedly accompanied by sinking elsewhere, for a very similar exotic fauna appeared simultaneously in the American, the European, and the Asiatic region, and mingled with the preëxisting local faunas, giving one of the most distinctive paleontologic zones yet known,

During the Lower Trias the Arctic, the American, and the Oriental regions had closely allied faunas, and might be grouped together in contrast with the Mediterranean. At this time of transgression and readjustment of geographic boundaries we have the widely distributed fauna of the *Meekoceras* zone, distinctly recognizable in India, Siberia, and western America.

[1] J. P. SMITH: JOUR. GEOL., Vol. II, No. 6, 1894, The Metamorphic Series of Shasta County, California.

The Middle Triassic faunas seem to have been largely endemic, because the waters of that time were stable; thus there are no horizons that are directly comparable in distant lands. But again the Upper Trias ushered in a period of transgression and invasion, and the faunal zone of *Tropites subbullatus* appeared simultaneously in the Mediterranean region, in the Himalayas, and in California, with many genera and species common to these countries, exotic in all, and with no previous record to show their origin.

The geographic provinces of Jurassic time have been grouped by Neumayr[1] in two great regions, the Boreal and the Central Mediterranean, and further he has traced out the distribution of climatic zones of that time in the Boreal type, the North Temperate type, the Alpine or Equatorial, and the South Temperate. The western American province belonged to the Central-Mediterranean region and to the North Temperate climatic zone during Lower and Middle Jura, but with the beginning of the Upper Jurassic a great change took place in physical and faunal geography that connected the western American province for a time with the Boreal region. As a consequence of this the faunal zone of *Cardioceras alternans* and *Aucella pallasi* may be traced through Russia, Alaska, and California.[2] The disturbance that caused this invasion may easily be traced in the transgression eastward of the sea on the land that began in northern Europe already in Middle Jurassic, bringing down from the northwest a cold current that permitted the Boreal fauna to make its way into temperate latitudes on the western coast of North America.

The study of the distribution of fossil faunas as influenced by climate was begun by Ferdinand Roemer,[3] who recognized the fact that the Cretaceous of western Europe was similar to that of the Atlantic region in America, and that the faunas of southern Europe, northern Africa, Texas, and Mexico had much in

[1] Denkschr. K. Akad. Wiss. Wien, 1883, Klimatische Zonen während Jura und Kreidezeit.

[2] J. P. Smith: Jour. Geol., Vol. III, 1895, Mesozoic Changes in the Faunal Geography of California.

[3] Kreidebildungen von Texas, 1852.

common. These differences Roemer ascribed to climate, noting that then, as now, the isothermal lines came much further south in eastern America than in Europe.

It has been shown that at the beginning of Cretaceous time the faunal relations of the west coast of North America were still with the Boreal region, as in the Upper Jurassic. But this did not last long, for even before the end of the Knoxville epoch this fauna had died out, and was replaced by immigrants from another region. At first there were only a few stragglers, but soon the rich fauna of the Horsetown stage or Gault made its appearance, of a type precisely like that of southern India, and eastern Africa. A similar association of genera and species is also known in the European region, where it seems to have been endemic, and from which it probably reached the rest of the world by migration. This incursion of exotic faunas marks the last great period of readjustment of the geologic column in various parts of the world, and is therefore of the utmost importance in correlation. The kinship of the western American faunas to the Indian was stronger than that to the eastern American almost until the end of the Cretaceous, when a similarity to the interior province began to show itself. This change culminated in Eocene time, in the zone of *Venericardia planicosta*, when the barrier between the western and the interior Cretaceous provinces was temporarily removed, and through the Atlantic there was direct connection with the European waters. This is the last interregional zone, but it marked an era of retrogression of the sea, rather than of transgression, and since that time the marine provinces and regions correspond closely with the existing boundaries of temperature and shore lines.

Dispersion of marine animals in past and present.— Theoretically, pelagic faunas would be the best means of correlating distant regions; but in all probability we have no fossil pelagic faunas. J. Walther suggests that in the widely dispersed species of Mesozoic ammonites we have virtually a preservation of pelagic animals, or at least that their shells floated after death, and were distributed all over the earth by marine currents. This

sounds plausible, viewed in the light of what we know of the distribution of *Spirula*. But the living Pearly Nautilus is not distributed by currents away from the region of its present habitat, and in studying fossil faunas we find that the cephalopods had little wider distribution than brachiopods and pelecypods, animals usually fixed in station during most of their life, and able to migrate only during the larval stage. Another argument against the current-distribution hypothesis has been brought up by Dr. A. Tornquist, that the fossil ammonites of Jurassic and Cretaceous age are distributed approximately according to climatic zones.

The geologic record has been kept by the inhabitants of submerged continental or island shelves, and their dispersion cannot have been accidental or individual, but was faunal. The means and the reason for this migration are furnished by changes in physical geography. Any rising or sinking of shore lines would drive the inhabitants from their dwelling places; any newly opened connections between regions that before were separated would cause an intermingling of different faunas. An example of this is going on before our eyes today; the Red Sea and the Mediterranean have faunas as distinct as if they occurred on opposite sides of the world, but since the opening of the Suez Canal, intermigration has already begun, and in this present age will be recorded an inter-regional invasion comparable with those that took place in remote geologic time. And no doubt to some future geologist this record will be just as clear as those we have of similar changes in the past. Each great change in the outlines of continents must also have caused great changes in the direction of marine currents. Thus in the great subsidence of land in northern Eurasia that caused the transgression of the Upper Jurrasic sea must have opened the way for the cold current that came from the northwest along the Pacific shore of North America, bringing a Boreal fauna into temperate latitudes. Something similar to this would happen if, at some future time, the old dismembered Antillean continent were raised to its former position; the Gulf Stream could not enter the warm waters

of the Carribean, would be deflected, and the waters of the northwestern coast of Europe would be chilled.

The horizons of America that represent periods of instability of shore lines are the very ones that contain the remains of exotic faunas, such as those of the *Cuboides* zone, the *Intumescens* zone, the Chouteau limestone, the St. Louis beds, or the shifting zones of the Coal Measures. These migrations must all have been faunal rather than individual, and can have been due only to physical agencies acting slowly and on a large scale. No extraordinary catastrophies need be appealed to as an explanation of this, for similar phenomena are always going on before our eyes, in the slow but ceaseless rising of some shores and sinking of others.

Land masses present an insuperable barrier to marine animals; but if the bodies of land are short, and do not reach into polar waters, animals can easily pass around the ends. Thus the molluscan fauna of the Mediterranean does not differ greatly from that of the English waters, because in the passage around the peninsula of Spain, animals remain in temperate waters and under nearly the same conditions. East and west land masses would, therefore, not be effectual barriers, since they would not be so likely to extend into frigid waters nor into very great differences of temperature. An example of this is the similarity of marine faunas on the east and the west coast of Australia.

On the other hand, the Isthmus of Panama separates two faunas absolutely distinct from each other, although in the same latitude, and under the same climatic conditions. Also the Isthmus of Suez separates two totally distinct faunas, but these belong to different regions and even to different climatic zones, brought near together by the narrow strip of the Red Sea. A similar case is known in the Jurassic formation, where the fauna of western Europe stands sharply contrasted with that of Russia; even the characteristic genera are distinct, and this too in latitudes not very different. These two types represent two seas of different climatic zones, separated by a strip of land during the later portion of Jurassic time.

That climatic zones alone are to-day partial barriers to migrants along the coast is shown by the difference in faunas living in northern and in southern latitudes on north-south shores. We would expect cold water species to be able to cross climatic zones more easily than those adapted to warm water. But we know of no cases where equatorial faunas have passed through arctic regions, and even passages from tropical into temperate waters must have been exceedingly difficult, for a fall of a few degrees below the temperature favorable to life must be a great deal more destructive than a rise of many degrees. At present we have no means of testing this statement, but facts brought to light by geology confirm it. The Jura of western Europe and of the Argentine Republic have practically the same fauna, which, in reaching one of these regions from the other, must have passed from temperate waters through tropical, and into temperate seas again. The genera *Lytoceras* and *Phylloceras* are common in the Neocomian beds of southern Europe; but although these waters were undoubtedly connected with those of northern Europe, those genera are lacking in the latter region. Also in the lower part of the Californian Knoxville beds, the above mentioned genera are unknown, and come in only higher up where the first members of the tropical Indian fauna began to appear.

By far the greater part of marine animals live near the shore and are unable to exist under other conditions. To these an abyssal sea is as impassable a barrier as a continent. The marine faunas of the southern ends of Africa, South America, and Australia are in approximately the same climatic conditions, but although they are connected by open seas, they are as different as if they were in totally disconnected basins. But an east-west sea affords good opportunity for passage from one side to the other by slow passage along the margin. The present fauna of the Mediterranean is good evidence of this, the animals of the European shores not differing appreciably from those of the African. The Mesozoic faunas of the ancient Central-Mediterranean sea owe their great distribution to this fact, for nearly the

same conditions existed then as in the present Mediterranean, except that the extent was vastly greater.

And even on opposite sides of great north and south oceans there are usually many species in common; the Atlantic shore American fauna has many European species, and the Pacific shore harbors some from Asiatic waters. Their passage was affected in most cases along continental borders that have since been obliterated by subsidence and erosion. We have an abundance of geologic and biologic evidence that just such changes have taken place in comparatively recent time, for example, the dismemberment of the old Antillean continent since Tertiary time. Also in the Indian Ocean there existed a continent in late Paleozoic and early Mesozoic time, connecting Australia with Asia; and Wallace[1] has shown that even since the Tertiary, Australia has been connected with many of the now separated islands of the Indian Ocean, although cut off even then from Asia.

The occurrence of identical or very closely related species in widely separated localities is good evidence of migration from one of these localities to the other, or from a third region to both. In many cases faunas even appear unheralded by local ancestors; these are exotic, having been brought in by migration from outside regions. In the chapter on paleontologic zones many of these exotic faunas have been enumerated, and the general statement made that their appearance invariably coincides with a time of shifting of the boundaries of land and sea, and consequent opening of new connections.

Colonies.— It is often noticed that species or faunas are intermittent in occurrence, especially when the character of the sediments is shifting. When sands are being deposited in shallow waters certain animals find their favorite habitat there, and when subsidence cuts off the clastic sediments and the waters become clear, other animals hold sway. Such faunal changes are due to the facies of sedimentation, but both sorts lived in the same

[1] Geographical Distribution of Animals, Vol. II, The Australian Region, pp. 387–485.

province and near together. But intermittence of occurrence is occasionally noted when it cannot be due to difference of facies. Just such a case is the reappearance of a Chouteau fauna in the Osage horizon of Missouri,[1] or the reappearance of Devonian types in the St. Louis beds at a number of places in the United States. In the Jura of northern Europe, according to Neumayr,[2] the genera *Lytoceras* and *Phylloceras* appear only sporadically, being lacking in sixteen zones; and even the known species there do not belong to a genetic series. But in southern Europe these genera appear plentifully in all the zones, and seem to represent genetic series. Their migration northward at several successive periods is thus clearly established. In these same beds *Amaltheus* also appears intermittently, but no region is yet known where *Amaltheus* developed continuously. Among the Jurassic ammonites of northern Europe there are a number of other cryptogenic types, many of which coincide with the *Amaltheidae* in their appearance, and thus probably came from the same region.

Today, when the struggle for existence becomes too severe for a species it disappears. In geologic history, too, a species has a certain length of life and dies out, never to reappear. This has given rise to the theory that species, like individuals, have a limited life, and that in time they reach a stage of development where they can go no further, and then of necessity die out. This would all be very well if species dropped out one at a time and contemporaneously all over the earth, but in reality they come and go by faunas. A study of the successive fossil faunas of the Pacific coast region has shown that while there may be a nearly perfect stratigraphic series, the faunal succession is broken, so that each fauna appears unheralded, in a way that would have delighted the heart of Cuvier. But we often find the forerunners of these unheralded faunas in older beds in other regions; this gives the rational explanation of the phenomenon,

[1] C. R. Keys: Amer. Jour. Sci., Dec. 1892, p. 447.

[2] Jahrbuch K. K. Geol. Reichsanstalt, Wien. Bd. 28, 1878. Ueber unvermittelt auftretende Cephalopodentypen in Jura Mittel-Europas.

migration due to the removal of barriers.[1] It would seem, then, that changes in physical geography have been the chief cause, not only of migration, but also of extinction of faunas; and this becomes all the more probable when we reflect that species have not been extinguished contemporaneously over the earth.

Remarkable cases of survivals of types have long been known, as of *Trigonia* in the Australian waters, and of *Pholadomya* in the Antilles. Survivals of faunas, too, are continually coming to light. A number of species that on the west coast of the United States are known only as fossils in Pliocene and Quaternary strata, are still living elsewhere. Dall[2] has shown that a large proportion of the Pliocene and even Miocene invertebrates of the southeastern states are still found living in the archibenthal region off the present coast. Similarly, it has been shown by Walcott[3] that in the Great Basin Carboniferous province many Devonian types persisted long after they had become extinct elsewhere, and this has been used by H. S. Williams[4] to explain the reappearance in the Mississippi valley St. Louis beds of a fauna previously thought to have been extinct since the very beginning of Carboniferous times.

Dr. David Brauns[5] cites from the late Pliocene or early Pleistocene of Japan a large number of species that are still flourishing on the western coast of America, and some are found living there that in western America are known only as fossils. Thus in the future some confusion might originate by correlating these beds with those now forming.

It is well known that during the Upper Carboniferous there flourished in India, South Africa, and Australia the *Glossopteris* flora, a type that in other regions was characteristic of Mesozoic instead of Paleozoic beds. Waagen[6] has suggested that the

[1] J. P. SMITH: JOUR. GEOL. Vol. III, 1895. Mesozoic Changes in the Faunal Geography of California.

[2] Bull. Mus. Comp. Zoöl., Vol. XII, No. 6, p. 186.

[3] Mon. VIII, U. S. Geol. Survey.

[4] Amer. Jour. Sci. III Ser., Vol. XLIX, pp. 94–101.

[5] Mem. Science Dept. Univ. of Tokio, No. 4, 1881, p. 77.

[6] Pal. Indica. Salt Range Fossils. Geological Results, p. 240.

glaciation in this region near the beginning of Permian time killed off the Paleozoic flora and allowed the *Glossopteris* flora to get a foothold earlier than was the case where there was no glaciation. Such phenomena approach the nature of catastrophes, and show that Cuvier's doctrine was not altogether wrong after all, and he probably had something like this in mind, although not formulated. These facts, too, show that the principles on which Barrande's[1] doctrine of "colonies" was founded were right, even though it has since been found that the particular cases on which he based his colonies were only younger rocks carried into the midst of older beds by dislocations. Barrande's idea seems to have been that in certain separated basins a new type of life would be introduced before it appeared elsewhere, and that by changes in physical geography these precursor faunas would be intercalated with those of older type. The modern doctrine of colonies, on the other hand, is that older faunas have often been preserved in places where no great changes have taken place in the conditions necessary for their life, and that these older surviving faunas have been mingled as anachronisms with the younger through immigration made possible by the removal of barriers, or changes in the direction of ocean currents.

Synchronism vs. homotaxis.—Forms are said to be heterochronous when they occur at different horizons, in different regions. Now it is possible that the same species seldom occurs at exactly the same time in two widely separated places; it must originate at the one and migrate toward the other, or migrate to both from a third place. This would take time, and it is supposable that the species might be entirely extinct at the point of origin before it reaches its second habitat, or become so greatly modified on its journey as to require a new name, or a number of new names. A case in point is the migration and development of *Ceratites nodosus* in the middle Trias of Germany. In the North-German basin this species is exceedingly common in the Muschelkalk, and exceedingly variable, but the boldest species-maker has not yet dared

[1] Système Silur. du Centre de la Bohême, Vol. I, p. 73 et seq.

to split it up into a number of species, because there are transitions between all the varieties. Dr. A. Tornquist[1] has recently shown that *Ceratites nodosus* also occurs in the upper Muschelkalk of the southern Alps, and that there the varieties lack the transitions, and thus may be given names to mark this transformation. The immediate varieties never reached the Alpine province, or else the modification took place on the way. The zone of *Ceratites nodosus* is thus inter-provincial in extent.

A somewhat similar case is known in the distribution of certain living species of the genus *Purpura;* in the English waters *Purpura lapillus* is common and exceedingly variable, but no constancy can be traced in these variations, the influence of temperature, sea bottom, and food supply being so evident, and the transitions so gradual that no subdivision of the species is attempted. Some of these same varieties are found on the western coast of America, but without the transitions, and so they are called by a number of specific names, which, although they are given to forms locally distinct, can certainly be only synonyms of *Purpura lapillus.* At some not very distant time these forms migrated westward from the Atlantic waters, and either varied on the journey, or else the intermediate forms did not succeed in reaching the Pacific region.[2] Here is certainly an interregional migration where a species is still living in the waters where it originated.

The genus *Clymenia*, according to J. M. Clarke,[3] appears in the *Goniatites intumescens* zone in New York ; in Europe *Clymenia* is wholly unknown in the *Intumescens* fauna, but is the characteristic form of the next higher division of the Devonian, where the *Intumescens* fauna was already extinct. In North America *Pronorites cyclolobus* and *Conocardium aliforme* appear in the Lower Coal Measures, while they flourished in Europe in the zone of

[1] Zeitschrift d. Deutschen Geol. Gesell. Bd L. Heft 2, 1898, and Heft 4. 1898. Neuere Beiträge zur Geol. und Paläntol. der Umgebung von Recoaro and Schio (im Vicentin).

[2] A. H. Cooke, Mollusks, 1895, pp. 90 and 363.

[3] Am. Jour. Sci., Ser. 3, Vol. XLIII, p. 57.

Goniatites striatus of the Mountain Limestone. The genera *Gastrioceras* and *Paralegoceras* appeared in America in the zone of *Goniatites striatus*, while they are not known in Europe before the Coal Measures. But the accompanying faunas in these regions are, in the main, correlative, and so the heterochronous appearance can be detected.

In the Upper Trias, Karnic stage, of California *Halorites* occurs, although in both the Alps and the Himalayas it is characteristic of the higher Noric stage. Also in California *Trachyceras* and *Protrachyceras* occur in the zone of *Tropites subbullatus*, mingled in the same hand specimen with typical species of the *Subbullatus* fauna; in the Alps and in the Himalayas *Trachyceras* and *Protrachyceras* are older than the *Subbullatus* zone, and are never found in it.

Now, when we have fossil species or short lived genera common to two regions, are the strata of these regions to be considered as synchronous? Huxley[1] advanced the theory that migration from one region to another would consume so much time that a fauna might become extinct in one region before it reached the other, and that since we determine the age by these faunas, the time of deposition of strata assigned to the same geologic age might be very different. Thus a Silurian fauna might survive in one region, while a Devonian fauna flourished in a second, and a Carboniferous fauna might be beginning in a third region. But the fossiliferous beds are Silurian, or Devonian, or Carboniferous in the faunal sense. This relation Huxley called *homotaxy*, and most geologists have accepted without question the validity of the hypothesis.

Viewed in the light of modern distribution of fauna, there must be something in it. The present Australian fauna is often cited as an example of unreliability of the time scale when based on faunas, as a survival of Quaternary life at the present time; it certainly is peculiar, for the continent has been totally cut off from other regions since early Mesozoic time. This fauna, however, has not dropped behind; it has gone on specializing in

[1] Presidential address. Quart. Jour. Geol. Soc. London, 1862. Vol. XVIII.

TABLE OF INTERREGIONAL ZONES

		EUROPE	NORTH AMERICA	ASIA
TERTIARY	Pliocene			
	Miocene			
	Eocene	Zone of Venericardia planicosta	Atlantic Slope ↘ Gulf Region ↘ California ↘ Oregon	
CRETACEOUS	Upper	Zone of Hippurites	Texas ↘ Mexico	
		Zone of Schloenbachia	West coast ↘ Interior	India
	Lower	Zone of Acanthoceras mamillare	West Coast	India
		Zone of Aucella terebratuloides	California ↘ Alaska	Siberia
JURASSIC	Upper	Zone of Cardioceras alternans	California	India ↘ Siberia
	Middle			
	Lower	Zone of Arietites	Nevada ↘ California	Japan ↘ Island of Rotti in the Indian Ocean
TRIASSIC	Upper	Zone of Tropites subbullatus	California	India
	Middle	Zone of Ceratites ↘ Beyrichites	Nevada	India ↘ Siberia
	Lower		Zone of Meekoceras gracile in California ↘ Idaho	Siberia ↘ India
CARBONIFEROUS	Permian	Zone of Neoschwagerina craticulifera in Sicily ↘ Russia	Texas	India ↘ China
	Coal Measures	Zone of Gastrioceras marianum	Mississippi Valley ↘ Texas	? Beds of Lo Ping China
		Zone of Gastrioceras listeri	Mississippi Valley	
		Zone of Glaphyrites keyserlingianum	Arctic America	Sumatra ?
	Mississippian (Carboniferous)	Zone of Goniatites striatus	Mississippi Valley ↘ Texas	
		Zone of Productus giganteus in Russia ↘ Belgium	California	Siberia ↘ China
		Zone of Agoniatites latilobus	Mississippi Valley	
DEVONIAN	Upper	Zone of Manticoceras intumescens	New York	Siberia ?
		Zone of Rhynchonella cuboides	New York	Siberia
	Middle			
	Lower			
SILURIAN	Upper	Zone of Calymmene blumenbachi	Mississippi Valley ↘ New York	
	Lower			
CAMBRIAN	Ordovician	Olenus fauna	Canada	
	Paradoxides	Paradoxides fauna	United States ↘ Canada	
	Olenellus	Olenellus fauna	United States ↘ Canada	

its own lines, and in all the geologic ages to come will never reach the development of life as we know it elsewhere in the Era of Man.

But is the marine fauna on the Australian shores markedly different from that in other parts of the Indian Ocean, and has that of the Indian Ocean no near relationships with the outside world? There are faunal provinces in these, with local characteristics, but with gradual transition from one province to another, and from one region to another through adjacent provinces. Thus the Australian waters show a gradual transition in fauna to the China Sea, and that to the Japanese marginal fauna, which, in turn, show many species in common with the west American region.

If, then, the modern Pacific and Indian Ocean marginal faunas were fossilized it would be no great task to correlate them, although the western coast of America might not show a single species in common with Australia. The laws that govern the distribution and intergradation of marine faunas are the same now as they have always been. All stratigraphic classification and all paleontologic correlation are based ultimately on fossil marine faunas.

The reality of correlation.—The geologic succession of faunas has some irregularities and anomalies, as shown above, but the displacements of the time scale are too slight and the uniformity in various separated regions too great to lay much stress on homotaxis as opposed to synchronism. While homotaxial strata are not necessarily synchronous in years nor in centuries, the cases cited above show that they often are actually contemporaneous. But even if they were not, years and centuries count little as compared with the time back to the Quaternary, and still less with the great stretches of time in the Paleozoic. And if a Silurian fauna still persists beyond its time by reason of local favoring conditions, it is merely a transient exception, for interregional migration soon readjusts the faunal scale in harmony with the time scale. The survivals of species or faunas are the exception rather than the rule, and such anachronisms can be detected in the past as well as now.

If there had ever been any great displacement of the faunal scale from the time scale, this would have been cumulative, and eventually the paleontologic column of America would have been out of harmony with that of Europe. But the successive faunas from Lower Cambrian to Pleistocene are in perfect accord in all the regions of Europe, Asia, Africa, America, and Australia; there are constantly recurring small displacements due to temporary isolation, and constantly recurring readjustment due to reopened or newly-formed connections, giving interregional correlative faunal zones through migration. These zones may be, and often are, actually synchronous. The periods of endemic development may be homotaxial, but the zones of readjustment are correlative in the strictest sense.

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CONTRIBUTIONS FROM WALKER MUSEUM. I.

THE VERTEBRATES FROM THE PERMIAN BONE BED OF VERMILION COUNTY, ILLINOIS.

THE material described and figured in the present contribution comprises a portion of the vertebrate material of the Gurley Collection of Fossils in the Walker Museum, at the University of Chicago. The material is of extreme interest from both an historical and a scientific standpoint, its discovery being the first evidence of the occurrence of Permian reptiles in North America. A few isolated bones were submitted to Professor Cope, and with his usual keen insight he recognized their character and their value, and by his interest he stimulated the work of their careful collection and preservation. To Mr. Gurley is due the credit for a careful and exhaustive exploration of the "bone bed," and the preservation of the material.

Many of the forms were described by Cope in the files of the Proceedings of the Philadelphia Academy of Natural Science, and the American Philosophical Society, but only a few illustrations of the intercentra of *Cricotus* have ever been published. It was his intention to publish full descriptions of the forms, with illustrations, and for this purpose plates had been prepared for an article in one of the government publications, which was never issued. Much of the material is fragmentary, and nearly all the bones were found isolated, so that it is especially difficult to identify the species from the descriptions alone. Especially is this true when the specimens to be compared come from another locality.

In the present paper the original descriptions have been reproduced, wherever they would serve the purpose, along with some additional notes, and the specimens figured. In many instances the figures have been copied from those prepared by Cope for his unpublished work. A few of the specimens

described by Cope are now missing from the collection, and so cannot be figured.

Several specimens are preserved in the collection which were never described by Cope. I have refrained from giving new names to these, as it is altogether probable that the seemingly new forms are but portions of the skeleton of animals that have been named from other parts of the skeleton. The numbers given at the close of each description, are the record numbers of the Paleontological collection in Walker Museum, at the University of Chicago.

Janassa strigilina Cope. Plate I, Figs. 1*a*, 1*b*, 1*c*.

Strigilina linguæformis Cope, 1877, Proc. Am. Phil. Soc., p. 53. (Specific name preoccupied in 1868 by Atthey.)

Janassa strigilina Cope, 1881, Am. Nat., p. 163.

Janassa strigilina Woodward, 1889, Cat. Foss. Fishes Brit. Mus., Pt. I, p. 38.

Generic characters: "The tooth is a flat, osseous plate, whose outline is pyriform, the wider end recurved in one direction as the transverse cutting edge; the other extremity narrowed and recurved in the opposite direction as the root. The side from which the cutting edge arises is crossed by numerous plicæ from the base of the root to near the base of the cutting edge; the opposite side is smooth."

Specific characters: "The plicate surface terminates behind in a median angle, at the base of the root. There are eight plicæ which all cross the plane, excepting the sixth, which is interrupted in the middle by the strong angulation of the seventh, which touches the fifth. The lateral extremities of the right are in contact with the base of the recurved cutting portion. The latter is convex transversely, leaving a smooth surface between it and the eighth plica. The smooth side of the tooth is shining, and there is a shallow fold, which passes around its side and crosses just at the base of the recurved cutting lamina."

MEASUREMENTS.

"Total length of the plane	.008	m
Width at base of the cutting lamina	.006	
Width at the base of the root	.004	
Thickness of plane portion	.0015	"

[No. 6500.]

Janassa gurleyana Cope. Plate I, Figs. *2a*, *2b*, *2c*.

Strigilina gurleiana Cope, 1877, Proc. Am. Phil. Soc., p. 191. (Pal. Bull., No. 26.)

Janassa gurleiana Cope, 1881, Am. Nat., p. 163.

Janassa gurleiana Woodward, 1889, Cat. Foss. Fishes Brit. Mus., Pt. I, p. 39.

"The tooth is quite small, its length only equaling the width of the known tooth of *S.* (*Janassa*) *linguæformis*. It is also narrower in proportion to the length. The root and the cutting edge are turned in opposite directions as in the other species. The principal difference between the two is seen in the character of the transverse ridges or crests of the oval face. There are two crests less, or five, with a delicate basal fold, making six, while, counting the fold, there are eight in *S.* (*Janassa*) *linguæformis*. The anterior ridge is transverse; the others slightly convex backwards, and all are equidistant and uninterrupted, which is not the case in the older species. They are also of different form, being distinct ridges with anterior and posterior faces similar. In *S.* (*Janassa*) *linguæformis* the anterior face only is vertical, the posterior descending very gradually, the whole forming a series of steps.

"Length of the ridged face, .0060^{m}; width anteriorly, .0035^{m}; width posteriorly, .0020^{m}."

[No. 6501.]

Pleuracanthus (**Orthacanthus**) **quadriseriatus** Cope. Plate I, Figs, *3a*, *3b*.

Orthacanthus quadriseriatus Cope, 1877, Proc. Am. Phil. Soc., p. 192. (Pal. Bull., No. 26.)

Pleuracanthus quadriseriatus Woodward, 1889, Cat. Foss. Fishes Brit. Mus., Pt. I, p. 9.

Represented in the collection by imperfect radial spines. Both Newberry and Cope remark that it is very likely that the spines called *Orthacanthus* may belong to the the same fish as the teeth called *Didymodus* (*Diplodus*), and as the teeth are distinctly referable to the genus *Pleuracanthus Ag.*, it is perhaps best to follow Zittel in regarding all three names as synonyms of *Pleuracanthus*. The teeth and spines are found in close connection. The species here described differs from the *O. gracilis* of Newberry in having the denticles shorter. The description given by Cope is as follows: "The spine is wider than deep, and the series of denticles are widely separated. The surface between them is gently convex and smooth. The anterior face is strongly convex, and presents at each side two shallow furrows. The external groove is divided by a series of thin longitudinal denticles which are smaller than those of the principal row, and which are

sometimes confluent at the base. The principal denticles are closely placed, stout, acute, and recurved.

"Transverse diameter of shaft .0035^{m}; antero-posterior diameter .0025^{m}; the portion of the shaft preserved is straight."

It is noticeable that the denticles of the outer row become confluent in a low ridge on the lower portion of the spine.

[No. 6502.]

Pleuracanthus (Orthacanthus) gracilis Newb. Plate I, Fig. 4.

Orthacanthus gracilis Newb., Geol. Surv. Ohio, Pal., Vol. II, p. 56. Plate LIX, Fig. 7.

Orthacanthus gracilis Newb., Cope, 1881, Am. Nat., p. 163.

"Spine small and straight, about three inches long, very slender and acute; section circular at base, posterior face and sides flattened above, the angle inclosed by them set with acute, recurved, compressed denticles throughout the upper two thirds of the entire length; surface smooth or finely striate longitudinally."

The name *Orthacanthus* was used by Newberry only provisionally for spines which were supposed to belong with teeth called *Diplodus*, and was to be suppressed when the two should be found together.

It is noticeable that the denticles are fewer and larger than those on the spine of *P. quadriseriatus*, and that there is but a single row of denticles on each side.

[No. 6503.]

Pleuracanthus (Didymodus) compressus Newb. Plate I, Figs. 5*a*, 5*b*, 5*c*, 5*d*.

Diplodus (?) *compressus* Newb., Cope, 1877, Proc. Am. Phil. Soc., p. 54.

Didymodus (?) *compressus* Newb., Cope, 1883, Proc. Phil. Acad. Nat. Sc., p. 108.

Represented in the collection by several imperfect teeth. Cope offered no additional description of the form, contenting himself with the statement that "one with a lateral and median denticles nearly complete, agrees pretty well with the species cited." In 1883 he substituted the name *Didymodus*, as the name *Diplodus* was preoccupied, having been used by Rafinesque for a genus of fishes.

The teeth are much smaller than the species of the same genus found in Texas.

Later several complete crania of the genus were obtained from Texas and described in detail by Professor Cope, Trans. Am. Phil. Soc., 1884, pp. 572–590, 1 plate (Pal. Bull., No. 38). In the American Naturalist of the same year, p. 413, the genus was made the type form of the new order *Ichthyotomi* of the *Elasmobranchii*.

The form is now quite usually recognized as belonging to the genus *Pleuracanthus* Ag., one of the common forms of the Carboniferous and Permian faunas of Europe and America.

[No. 6504.]

Thoracodus emydinus Cope.

Thoracodus emydinus Cope, 1883, Proc. Acad. Nat. Sc., Phil., p. 108.

Thoracodus emydinus Woodward 1889, Cat. Foss. Fishes Brit. Mus., Pt. I, p. 39.

"The form of the tooth or jaw on which this genus is proposed, reminds one of that of a *Diodon*, and also of one half of that of a *Janassa*. It appears to be the half of a bilateral plate, which is divided on the middle line by suture. Its form is somewhat that of the anterior part of an episternal bone of a tortoise. It consists essentially of a smooth border, separated from the remainder of the tooth by a transverse groove. The interior portion is, on the superior face (if the piece belong to the inferior jaw, and *vice versa*), transversely ridged and grooved, after the manner of the genus *Janassa*."

Specific characters: "The smooth border is wide above and below. Its edge is produced into a median projection, which is decurved. On the inferior surface it is marked by shallow grooves, which radiate from the groove which bounds it posteriorly, extending nearly to the free edge. Posterior to the bounding groove, the surface is smooth. The posterior surface above has its grooves concentric with the curved free margin. The ridges are narrow, and step-like in position, presenting their free edges backwards. There are no grooves other than these steps. They have an angular curve opposite to the angle of the free margin, and at the angle the groove which separates them is narrowed, while it widens at other points. Free edge of border thickened; surface everywhere smooth."

MEASUREMENTS.

"Length of fragment transversely	.014[m]
Length of fragment antero-posteriorly	.011
Width of border area at median suture	.005
Seven cross ridges	.005
Thickness at suture at cross ridges	.002 "

[This specimen is missing from the collection.]

Sagenodus vinslovii Cope. Plate I, Figs. 6*a*, 6*b*.

Ceratodus vinslovii Cope, 1875, Proc. Phil. Acad. Nat. Sc., p. 410.

Ceratodus vinslovii Cope, 1877, Proc. Am. Phil. Soc., p. 54.

Ptyonodus vinslovii Cope, 1877, Proc. Am. Phil. Soc., p. 192. (Pal. Bull., No. 26.)

Sagenodus vinslovii Woodward, 1891, Cat. Foss. Fishes Brit. Mus., Pt. II, p. 262.

Sagenodus vinslovii Williston, 1899, Kans., Univ. Quart., Series A, p. 176.

"The crown of the tooth is in general outline an oval, wider at one end than the other, the inner border gently convex and entire. The outer border is marked by six shallow notches which are separated by as many sharp, compressed projections. The emarginations and denticles are the termini of corresponding grooves and ridges, which radiate from a smooth space along the inner margin of the crown. From this plane the grooves gradually deepen to the margin; the separating ridges are acute and without irregularity or serration. The base or root of the tooth is quite wide. Externally it extends beyond the border of the crown at the notches, and has projections corresponding to the denticles, from which it is separated by a horizontal notch. On the inner side the base extends like a shelf beyond the posterior half of the crown, and is produced backwards beyond its posterior border. The inferior plane is concave in transverse section; the crown is plane in all directions."

MEASUREMENTS.

"Length of crown preserved	.021[m]
Width crown	.013
Length of root preserved	.022
Depth of root internally	.005
Depth of root externally	.003 "

"This *Ceratodus* (*Ptyonodus*) resembles the species described by Agassiz under the name of *C. parvus* and *C. serratus* from the English Trias, but differs from them in the shortness of the tooth-like processes. In none of the species do I find such a development of the basis on the inner side."

[No. 6507.]

Sagenodus vabasensis Cope. Plate I, Fig. 7.

Ctenodus vabasensis Cope, 1883, Proc. Phil. Acad. Nat. Sc., p. 110.

Sagenodus vabasensis Woodward, 1891, Cat. Foss. Fishes Brit. Mus., Pt. II, p. 261.

Sagenodus vabasensis Williston, 1899, Kans. Univ. Quart., Series A, p. 176.

"This fine species is represented by an almost perfect tooth. It is allied to the *C. fossatus* Cope, but is wider, and the crests do not radiate so equally, but are chiefly directed in one direction, as in most species of the genus. The *C. gurleianus* and *C. pusillus* are at once distinguished by the small number of crests, while the *C. periprion* and *C. dialophus* have a larger number of crests, and are otherwise different. *C. porrectus* differs less from it, but has only five ½ crests, while *C. vabasensis* has six ½. The ½ represents the small posterior (?) crest, which is double. This, with the next one, is directed slightly posteriorly; the fifth is at right angles to the long axis, and the anterior four extend more or less forwards. They are serrate nearly to their bases, but the teeth are obsolete on their basal halves. The straight part of the internal edge extends as far forwards as the fourth crest, and is continued posteriorly as a short process. No fossæ at ends of crests. Superior face of tooth wide and slightly concave. The anterior part of the first and second crests are broken away, so that it is impossible to say whether they are produced as in *C. porrectus*."

MEASUREMENTS.

"Length to marginal base of second crest	.024[m]
Width at marginal base of second crest	009
Width at fourth crest, inclusive of apex	.015
Width of posterior side	.010
Thickness at base of fifth crest	.005 "

[No. 6510.]

Sagenodus gurleyanus Cope. Plate I, Figs. 8*a*, 8*b*, 8*c*.

Ctenodus gurleyanus Cope, 1877, Proc. Am. Phil. Soc., p. 55.

Sagenodus gurleyanus Woodward, 1891, Cat. Foss. Fishes Brit. Mus., Pt. II, p. 261.

Sagenodus gurleyanus Williston, 1899, Kans. Univ. Quart., Series A, p. 176.

"This species is indicated by a portion of a tooth, which leaves the number of the ridges a matter of uncertainty. On this account its description might have been postponed, but that the distinctness of its characters render it clear that it cannot be placed with any other species. The crown, as in *Ceratodus* (*Sagenodus*) *paucicristatus*, is narrow and rather thick; but three

crests are present, all radiating in the same general direction, the longer close to the inner border. There was not more than one additional crest, or one and a rudiment, and these have probably the same direction as those which are preserved. The crests are sharp, elevated, and coarsely dentate; they are not decurved at the extremity, but cease abruptly with a projecting denticle, beneath which the basis is excavated by a shallow fossa. The inferior face is slightly concave, the internal wall vertical."

MEASUREMENTS.

"Greatest width	.008[m]
Depth at inner border	.005 "

[No. 6509.]

Sagenodus pusillus Cope. Plate I, Figs. 9*a*, 9*b*.

Ctenodus pusillus Cope, 1877, Proc. Am. Phil. Soc., p. 191. (Pal. Bull., No. 26.)

Sagenodus pusillus Woodward, 1891, Cat. Foss. Fishes Brit. Mus., Pt. II, p. 261.

Sagenodus pusillus Williston, Kans. Univ. Quart., Series A, p. 176.

"Form narrow, the width of the base about equal to the depth. The coronal portion is narrower than the base, because the inner face is oblique, forming an acute angle with the inferior plane. There are but four crests, of which the two longer are directed in one direction, and the two shorter in another. The interior ones of both pairs form a continuous crest which is convex inwards. The crests are straight, elevated and acute; each one supports two or three denticles, which are rectangular and little elevated. The longer ones project beyond the general outline; the shorter ones are less prominent at the extremities; all are obtuse in the vertical direction. The superior surface is smooth. The inferior is slightly concave in the transverse sense. The tooth on which this species is founded is the smallest yet obtained from the formation (Permian of Illinois). Length, .007[m]; width, .003[m]; depth at the inner crest, .003[m]."

[No. 6508.]

Sagenodus fossatus Cope. Plate I, Figs. 10*a*, 10*b*.

Ctenodus fossatus Cope, 1877, Proc. Am. Phil. Soc., p. 54.

Sagenodus fossatus Woodward, 1891, Cat. Foss. Fishes Brit. Mus., Pt. II, p. 261.

Sagenodus fossatus Williston, 1899, Kans. Univ. Quart., Series A, p. 176.

"Represented by a nearly perfect tooth of a general narrow and vertically thickened form. There are five crests, the largest three extended in one

direction, and the other two in the other. Between the last of the latter and the inner border is a rudiment of another in the form of a rugosity. None of the crests touch each other at their bases. At their extremities they curve rather abruptly downward, and do not project beyond the inferior plane, from which each one is separated by a deep fossa, whose mouth is a notch in its base. The crests are coarsely dentate, there being three or four teeth on each, and the grooves between them are marked by coarse transverse undulating grooves. The inner border is a deep vertical plane; the inferior face is narrow and concave in transverse section."

MEASUREMENTS.

"Total length	.022^{m}
Greatest width	.007
Depth at middle	.006 "

"It differs from the *C. serratus* of Newberry in its narrow form, small number of ridges and the very slight prolongation of their extremities."

[No. 6506.]

Sagenodus heterolophus Cope.

Ctenodus heterolophus Cope, 1883, Proc. Acad. Nat. Sc., Phil., p. 109.

Sagenodus heterolophus Woodward, 1891, Cat. Foss. Fishes Brit. Mus., Pt. II, p. 261.

Sagenodus heterolophus Williston, 1899, Kans. Univ. Quart. Series A, p. 176.

"This species is represented by a single broken tooth, which presents remarkable characters. It had apparently, when perfect, but three crests, which differ greatly in length, diminishing very rapidly from the first or marginal crest.

"The crest just mentioned is not only longer, but *much more* elevated than the others, except at the base, where the second crest is the highest. But while the first rapidly rises, the second retains its elevation, and then descends, forming a convex edge, of which the distal part is obtusely serrate. The proximal part of the first crest is worn by friction with the opposing edge of the opposite jaw into a sharp edge, below which its base is covered by a thin layer of the shining cementum which invests the teeth and sides of the second crest. The amount of this shinning layer is thus more extensive than in any other species of *Ctenodus* known to me. The third crest, judging by its base of continuity with the second, is very small."

MEASUREMENTS.

"Elevation of first crest at middle	.0095^{m}
Elevation of second crest at middle	.0065
Length of a tooth of second crest	.0020 "

[This specimen is missing from the collection.]

Sagenodus paucicristatus Cope. Plate I, Figs. 11*a*, 11*b*.

Ceratodus paucicristatus Cope, 1877, Proc. Am. Phil. Soc., p. 54.

Ptyonodus paucicristatus Cope, 1877, Proc. Am. Phil. Soc., p. 192. (Pal. Bull., No. 26.)

Sagenodus paucicristatus Woodward, 1891, Cat. Foss. Fishes Brit. Mus., Pt. II, p. 261.

Sagenodus paucicristatus Williston, 1899, Kans. Univ. Quart., Series A, p. 175.

"The single tooth representing this species is narrow in the transverse direction, but stout in vertical diameter. But four ridges are present, all of which have a single direction, but the shorter ones are the less oblique to the long axis of the tooth. They all extend into the inner border but become low as they approach it. Distally they are quite prominent, but do not project very far beyond the emarginate border between them. The inner border is plane and vertical, and without ledge; the inferior surface is concave in the transverse direction. The surface of the tooth is minutely and elegantly corrugated."

MEASUREMENTS.

"Length from the base of second rib - - - .017 m
Depth at base of second rib - - - - - .0045 "

[No. 6505.]

Peplorhina arctata Cope.

Peplorhina arctata Cope, 1877, Proc. Am. Phil. Soc., p. 55.

Theromorphous Saurian, Proc. Am. Phil. Soc., 1882, footnote to p. 461. (Pal. Bull., No. 35).

The species was based on an imperfect bone bearing small teeth. From its resemblance to the palatal teeth of *Peplorhina anthracina* the author refers it to that genus with the remark that "this course is open to modification should subsequent investigation require it." Later, in 1882, he remarks in a footnote; "*Peplorhina arctata* Cope from the Illinois Permian is not a *Peplorhina* but a *Theromorphous Saurian*."

The broken specimen originally described certainly has much the appearance of the small teeth which occur in the roof of the mouth of certain of the *Cotylosauria* and may very possibly belong there, but there is present in the collection a complete plate showing no sutural edges. It is certainly a plate from the mouth of a *Crossopterygian* fish, and as the description of the perfect portions of Cope's specimen applies very perfectly to it, it may best be considered under the original name. The applicable portion of the original description is as follows: "The convex surface (of the plate) is thickly

studded with teeth, which are not in contact with each other. Their size increases from one side of the bone to the other, and still more, from one extremity to the other. The crowns are swollen at the nearly sessile base, and contract rapidly to a conical and unsymmetrical apex. One side of the latter is slightly concave below the apex. The surface is shiny and distinctly grooved. Fractured crowns do not display any central cavity."

The present specimen is rather oval, one side showing a perfect convex outline and the other with three straight edges at large angles to each other. The whole plate is convex on the toothed side and concave below. The angulated border is thickened and roughened and the rounded border thin. The surface is covered with teeth, larger in the middle and on the thickened border than on the other edges. The plate is .0158^{m} long and .0114^{m} wide.

[Nos. 6511 (Cope's type) and 6512.]

Cricotus heteroclitus. Plate I, Figs. 12*a*, 12*b*, 12*c*, 12*d*, 13, 14.

Cricotus heteroclitus Cope, 1875, Proc. Phil. Acad. Nat. Sc., p. 405.

Cricotus heteroclitus Cope, 1877, Proc. Am. Phil. Soc., p. 64.

Cricotus discophorus Cope, 1877, Proc. Am. Phil. Soc., p. 186. (Pal. Bull., No. 26.)

Cricotus heteroclitus Cope, 1878, Proc. Am. Phil. Soc., p. 522. (Pal. Bull., No. 29.)

The genus was founded on some intercentra which were regarded as centra of the caudal region; it was not until 1878 that the true nature of the intercentra was made out. With the intercentra were a few other bones doubtfully referred to the same genus. That portion of the original description which is applicable to the bones as intercentra is as follows: "The caudal vertebra (intercentrum) best preserved is stout, discoidal in form, and deeper than wide. It resembles in form that of an herbivorous dinosaurian, but differs otherwise. The articular faces are deeply concave, the posterior most strikingly so; and the middle is occupied by a large foramen, whose diameter is about equal to that of the centrum on each side of it. The lateral borders of the posterior articular face are expanded backwards, and articulate with a bevel of the corresponding edge of the anterior articular extremity. In this way the vertebra combines the mechanical relations of the biconcave with opisthocœlian structures. These neural arches (hæmapophyses) are narrow and directed backwards; their bases are firmly coössified with the centrum." . . . . "On the inferior (superior) surface of the centrum (intercentrum) two shallow pits occupy considerable space. . . . ." It will be noticed that the describer had the intercentrum inverted; this fact was later understood by himself and certain drawings corrected. The structure of the skull and other

portions of the skeleton of the species are described by Cope in the Proc. Am. Phil. Soc., 1878, p. 523 and figured in the same, 1882, Plate II. The synonymy of *C. heteroclitus* and *C. discophorus* was also recognized by Cope in Proc. Am. Phil. Soc., 1878, p. 523.

[No. 6517 (the type specimen), 6518 (type of *C. discophorus*), 6519, and 6520].

Cricotus gibsoni Cope, Plate I, Figs. 15*a*, 15*b*, 15*c*.

Cricotus gibsoni Cope, 1877, Proc. Am. Phil. Soc., p. 185. (Pal. Bull., No. 26.)

Represented in the collection by several vertebræ, all of one form. Cope considered the type specimen as probably from the caudal region. He says, "On this vertebra there is no trace of diapophysis, and the neurapophysis rises from the external side of the superior face. The wall of the neural canal is not preserved, but the inference is that the diameter of the latter is large. This fact and the absence of definite chevron articulations leads me to doubt the caudal position of the vertebra; but the usual marks of the dorsal and cervical vertebrae are totally wanting from it. As in *C. heteroclitus*, the *foramen chordæ dorsalis* is large, its diameter being one third of the total. The articular faces descend steeply into it, that of one extremity more so than the other. The rim of the latter face is beveled outwards, the plane thus produced appearing on the inferior face something like the united faces of the chevron bones.

"The centrum is a little deeper than wide, and the inferior face is truncate so as to give a subquadrate outline. The inferior plane is concave, the concavity being divided by a longitudinal rib. The sides are somewhat concave, with a longitudinal rib at the middle. Diameters of centrum: vertical .010^{m}; transverse .009^{m}; longitudinal .008^{m}. Width of inferior plane .005^{m}; width above, including neurapophyses .008^{m}.

"As compared with *C. heteroclitus* this species differs in the presence of parallel ridges inclosing a median fossa on the inferior side of the centrum. The small size may be considered, but it is uncertain whether the two animals represented by the vertebrae are fully grown."

[Nos. 6521 and 6522.]

Cricotus sp. Plate V, Figs. 13*a*, 13*b*, 14*a*, 14*b*, 15, 16.

There are several phalanges of *Cricotus*. They are much stouter than those of *Clepsydrops;* even in the members of the distal series, where the phalanges are very short, they are still very stout, almost as broad as long. They show a delicate sculpture over the entire surface; the articular surfaces are less well defined than in the reptilian forms. In the middle series they

are longer in proportion than at either end, rather curved, flattened, and with the shaft little less in width than the extremities.

[No 6523.]

Diplocaulus salamandroides Cope. Plate I, Figs, 16*a*, 16*b*, 17*a*, 17*b*. Plate V, Figs. 17*a*, 17*b*, 17*c*, 17*d*.

Diplocaulus salamandroides Cope, 1877, Proc. Am. Phil. Soc., p. 187. (Pal. Bull., No. 26.)

Diplocaulus salamandroides Cope, 1882, Proc. Am. Phil. Soc., p. 451. (Pal. Bull., No. 35.)

Cope's generic description is as follows: "Vertebral centra elongate, contracted medially, and perforated by the foramen chordæ dorsalis; coössified with the neural arch, and supporting transverse processes. Two rib articulations one below the other, generally both at the extremities of the processes, but the inferior sometimes sessile. No neural spines nor diapophysis; the zygapophyses normal and well developed."

Specific description: "The surface of the centrum is smooth and is without grooves. The diapophyses and parapophyses are rather elongate, and are closely approximated one above the other. The superior process issues from the centrum opposite the superior margin of the articular faces. They stand equidistant from the extremities of the centrum, and are directed obliquely backwards. The anterior zygapophyses occupy the same level. The neural spine is a compressed longitudinal ridge; it divides behind, leaving a notch between the posterior zygapophyses."

MEASUREMENTS.

"Diameter of centrum	longitudinal	.0060[m]
	vertical	.0025
	transverse	.0025
Depth of centrum and neural arch		.0060
Width with transverse processes		.0070
Expanse of posterior zygapophyses		.0050 "

A portion of a small skull was in contact with one of the vertebra. The ramus of the jaw is shallow and stout, the external surface sculptured with inosculating lines. Teeth with cylindrical roots set in shallow alveoli. The crowns elongate, slightly compressed near the apex, and without grooves or lines.

In describing the vertebræ of *D. magnicornis* from Texas (Proc. Am. Phil. Soc., 1882, p. 453) Cope calls attention to the presence of zygosphene and zygantrum in that species; they are also present in the *D. salamandroides*, but are so small as to easily escape notice. The surface of the centrum is stated to be smooth in the Illinois species, this is largely due to weathering, as the more perfect specimens show the same beautiful sculpture as in the Texas forms,

The articulations for the ribs are separate in the cervical region, and become more and more closely united posteriorly. The resemblance between *D. salamandroides* and *D. magnicornis* is very striking, almost the only observable difference being in the size, the latter being from five to six times the size of the former. This statement is limited to the vertebral column, as the skull of the Illinois species is unknown.

In the Proceedings of the Am. Phil. Soc., 1882, p. 452 (Pal. Bull., No. 35), Cope gives a history of the classification of *Diplocaulus* and a summary of the characters of the genus as derived from specimens from the Permian of Texas.

[Nos. 6513, 6514, 6515, and 6516.]

Clepsydrops colletii Cope. Plate II, Figs. 1*a*, 1*b*, 1*c*, 2*a*, 2*b*, 3*a*, 3*b*.

Clepsydrops colletii Cope, 1875, Proc. Phil. Acad. Sc., p. 407.

Clepsydrops colletii Cope, 1877, Proc. Am. Phil. Soc., p. 62.

This genus was based on a series of vertebræ supposed to represent the cervical caudal and dorsal regions. With them were associated other bones, which in all probability did not belong to the same specimen, though they may have belonged to the same species of the genus. The vertebræ were compared with those of the *Cricotus*, or rather with the intercentra of *Cricotus*, as Cope was not entirely sure at the time of the amphibian nature of *Cricotus*. The original description of the vertebræ given by Cope to characterize the genus *Clepsydrops* is as follows: "They are deeply biconcave, the articular cavities being funnel-shaped and continuous, thus perforating the entire length of the centrum. In a dorsal vertebra the cavities communicate by a very small orifice, while in the posterior the median contraction of the canal is less marked. The posterior cavity is more gradually contracted than the anterior; in the latter the excavation is, in most of the vertebræ, but slight (except beneath the floor of the neural arch), until it falls rather abruptly into the axial perforation. In an (?) anterior dorsal it is as widely excavated at the border as the posterior funnel. Another peculiarity s the abscence of the processes of the centrum; and a small capitular articulation is seen sessile on the border of the cup of two of the dorsals.

"The axis has a singular form, owing to the tubular perforation which continues the posterior excavation to the anterior face of the centrum. There are three articular faces, a larger subround inferior and two smaller superior, which border the neural canal in front and below and are separated from each other and the inferior face by the perforation in question. The anterior face slopes obliquely backwards and downwards, and is convex in transverse section. There is no facet for the free hypapophysis of the odontoid, but it appears that the inferior articular face was applied exclusively to the centrum of the atlas, as in *Sphenodon*. But the axis differs from that of the

latter genus in the abscence of a coössified odontoid process. Either that element is entirely wanting or it consists of two pieces, interrupted in the middle by the notochordal foramen, and in correspondence with superior articular facets. There is no true hypapophysis of the axis, and the only indication of lateral processes is a small articular facet on each side on the lower part of the rim of the posterior funnel. These may have been related to rudimental cervical ribs. The neural arch is broken off.

The dorsal vertebræ have their sides somewhat contracted; in one specimen the inferior face is rounded, in another, which I suppose to belong to a different part of the column, it is longitudinally acute. In this and another dorsal, where the parts are exposed, the floor of the neural canal is interrupted by a deep fissure, which has a triangular shape with apex downward when seen in profile. This is due to the fact that the opposite halves of the centrum are united by the circumferences of the articular cups, which have in profile an X shape. The diapophysis does not project far beyond the base of the neural arch and is compressed. The caudals are elongate, and resemble, in the forms of the centrum and neural arch, those of *Lælaps*. The neural spines are not preserved, but if present were directed well backwards, bearing the posterior zygapophyses, since the arch stands only on the anterior three-fifths of the centrum. Chevron facets are not distinct, but two emarginations on the rim of the posterior face of one of the vertebræ indicate their existence. In other centra even these notches are wanting. The tail was evidently tapering. There is no evidence of the transverse fissures seen in *Sphenodon* and many *Lacertilia*, nor are there any diapophyses on the caudal vertebræ preserved.

Specific characters: "There is a shallow fossa in the entering angle between the superior and inferior articular facets of the front of the axis, and the centrum of the same is obtusely keeled below. The border of the anterior face of the dorsal vertebræ with keeled centrum is undulate. The obtuse inferior face of another dorsal is rugulose, and the edge of the face is not undulate. The inferior faces of the two caudals are marked with fine parallel grooves, while in another caudal and the (?) sacrals the same is smooth. There are some longitudinal ridges on the upper side of the larger caudal."

MEASUREMENTS.

"Length of centrum of axis	.006[m]
Width do. at middle behind	.008
Depth do. (oblique)	.010
Length centrum of sharp keeled dorsal	.014
Depth do. behind	.012
Width do. behind	.012
Length centrum rounded dorsal	.012
Depth do. behind	.011
Width do. behind	.010
Width neural canal do.	.004

Length centrum larger caudal	.014[m]
Width do.	.008
Depth do.	.008
Length smaller caudal	.010
Depth centrum do.	.007
Width do.	.007 "

[Nos. 6530 (type specimen), 6531, and 6578.]

Clepsydrops pedunculatus Cope. Plate II, Figs. 4*a*, 4*b*, 4*c*, 4*d*; Figs. 5*a*, 5*b*, 5*c*, 5*d*.

Clepsydrops pedunculatus Cope, 1877, Proc. Am. Phil. Soc., p. 63.

This genus was established on two vertebræ, a third cervical, and an anterior caudal, regarded by Cope as a dorsal.

"Both differ from corresponding vertebræ of *C. colletti* and *C. lateralis* (this is evidently a slip on the part of the describer; there is no *C. lateralis; C. vinslovii* is evidently referred to, as it was the only other species of the genus described at this date) in having elongate diapophyses for the attachment of the ribs. These are present in the other species, but are either very short, or sessile. The third cervical has a broad reverted anterior lip-like margin of the anterior articular face, which resembles the corresponding part in *C. lateralis* (*vinslovii*) in not being produced below. The median line is keeled, and there is a shallow longitudinal groove on the upper part of the sides. The posterior articular face is regularly funnel shaped. The diapophyses are very stout, and are directed a little downwards and strongly backwards. The articular faces are single, look downwards and outwards, and are wide above, and narrow below. The base of the neural canal is deeply incised, as in the other species."

MEASUREMENTS.

" Diameter of centrum	antero-posterior	.015 [m]
	transverse	.0125
	vertical	.012
Length of diapophysis above		.009
Diameter of diapophysis	vertical	.008
	antero-posterior	.005 "

In the description of the supposed dorsal attention is called to the long and slender diapophysis; it is evident that this is not a diapophysis, but an anchylosed rib with the distal broken portion inclined forward, as is characteristic of the anterior caudal ribs of the *Rhyncocephalia*. Speaking of other portions of the vertebra, the describer says: "There is no recurved rim of the articular extremities, but the surface does not pass regularly into the foramen chordæ dorsalis, but by an abrupt descent at its mouth. The

sides of the centrum are concave, and the inferior portion forms a prominent rounded rib."

MEASUREMENTS.

" Diameter of centrum	antero-posterior	.016[m]
	transverse	.015
	vertical	.016 "

[Nos. 6534 (type specimen) and 6535.]

Clepsydrops vinslovii Cope. Plate II, Figs. *7a*, *7b*, *7c*, *7d*.

Clepsydrops vinslovii Cope, 1877, Proc. Am. Phil. Soc., p. 62.

This species was based on a single cervical vertebra with which others were uncertainly identified. The specific characters given are as follows: "The inferior median line is a keel; some distance above it, the sides of the centrum are full, rising in a longitudinal angle. There is no constriction or fossa below the diapophysis as in *C. colletti*. The latter is anterior in position, is vertically compressed, and is curved forward for a short distance below. The posterior articular face is regularly funnel-shaped from the margin; the anterior face has a broad recurved lip. This passes around the inferior margin, which is not projected forwards as in *C. colletti*. The zygapophyses are well developed, and stand close together. The neural spine is compressed, and the basal portion points somewhat forwards."

MEASUREMENTS.

" Length of centrum		.011[m]
Diameter of posterior articular face	vertical	.009
	transverse	.009
Vertical diameter of diapophysis		.006
Expanse of posterior zygapophysis		.009
Antero-posterior diameter of base of neural spine		.005
Transverse diameter of neural arch		.006 "

[Nos. 6532 (type specimen) and 6533.]

Lysorophus tricarinatus Cope. Plate II, Figs. *12a*, *12b*, *12c*.

Lysorophus tricarinatus Cope, 1877, Proc. Am. Phil. Soc., p. 187. (Pal. Bull., No. 26.)

The type specimens consist of two vertebræ and a portion of a third. The generic characters given by Cope are as follows: "Vertebræ amphicœlian, perforated by the foramen chordæ dorsalis. Neural arch freely articulated to the centrum. Floor of neural canal deeply excavated. No processes or costal articulations on the centrum, which is excavated by longitudinal fossæ. Centrum not shortened." Specific characters: "Two centra and a portion of a third represent this species. The former are a little longer than wide and a little depressed. The facet for the neural arch is an elongate plane truncating the border of the fossa of the neural canal on each side,

for one half to three fifths the length of the centrum. Two deep longitudinal fossæ extend on each side of a median rib of the inferior face; and they are separated above by a narrower rib from another longitudinal fossa which is below the base of the neural arch.

MEASUREMENTS.

" Diameter of centrum	longitudinal	.0055^{m}
	vertical	.0038
	transverse	.0040
Length of facet for neurapophysis		.0035
Width of neural canal		.0020 "

This form differs very decidedly from any other in the collection in the prominence of the keel and the lateral ridges; they, or rather the fossæ between them, are developed to an extent that almost destroys the centrum, leaving but a very slender tube surrounding the notochord. A few centra of larger size show strongly developed keels and free neural arches, but much stouter proportions.

[Nos. 6526 (the type specimen; it is badly broken), 6527, and 6528.]

Archæobelus vellicatus Cope. Plate III, Fig. 1.

"*Species No. 4*" Cope, 1877, Proc. Am. Phil. Soc., p. 56.

Archæobelus vellicatus Cope, 1877, Proc. Am. Phil. Soc., p. 192. (Pal. Bull., No. 26.)

This genus is represented by teeth alone. In his discussion of the form Cope says, in the earlier paper, "there is nothing to prevent their (the teeth) reference to the *Lacertilia*." The generic description is as follows: "The form is conical, and the surface is not grooved nor furnished with prominent ridges. The interior is hollow, and the walls are composed of a few concentric layers without external enamel or cementum. The solid base to which it is attached is shallow, presenting smooth surface on the opposite side, which is deeply impressed by a longitudinal groove at one end." The specific description is given in the earlier paper: "The crown is conic, subround in section, and curved backward. There are no cutting edges, and the base is a little flattened in front and behind. On each of the faces thus formed, there is an open, shallow groove, sometimes obsolete. There are no other grooves or sculpture on the teeth. . . . . One of the specimens displays an extensive pulp cavity."

MEASUREMENTS.

	First specimen	First specimen	Second specimen
" Diameter of base	.004^{m} long	.008^{m} short	.005^{m}
		First specimen	Second specimen
Length of crown		.010^{m}	.015^{m} "

There are several specimens of the isolated teeth described by Cope in the collection, but in addition a considerable portion of a maxillary bone which

shows many points of interest. In all the single teeth, as described by Cope, they are attached to a portion of the jaw and unaccompanied by any other teeth, but there is posterior to the tooth a cavity which, as shown by the more perfect jaw, accommodated a second tooth larger even than the first. In the fragment of the jaw there are, first, three quite small teeth, and then, supported by a swollen portion of the rim, there are two very large canine teeth; posterior to these, three teeth about equal in size to those anterior to the canines, and then five smaller ones. As both ends of the piece are incomplete, it is certain that there were more teeth than here recorded. Several differences from *Clepsydrops* and *Dimetrodon* are apparent: first, the anchylosis of the teeth to the jaw, instead of being inserted in well defined alveoli; second, the presence of two enlarged canines instead of one, and third, the possible absence of the diastema anterior to the canines; for in the *Dimetrodon* the anterior teeth of the maxillary decrease to small size immediately and the notch of the diastema begins just anterior to the canine and below the external nares, but here, though the anterior tooth is almost below the nares, there is no sign of the beginning of the notch, if any existed. The teeth are all more or less rounded in section and show no sign of a cutting edge. In general appearance the jaw is much like that of the Pelycosaurians; *i. e.*, with a thin outer wall and a heavy shelf-like dentigerous edge.

Associated with the fragments of the upper jaws are several portions of the lower jaws showing the symphasial region. Some of the anterior teeth, about the third and fourth, seem to have been slightly larger than the others, but as such a small part is preserved it is impossible to say definitely. These fragments may have belonged to the genus *Clepsydrops*, and, indeed, the fragments of the upper jaws also.

[Nos. 6524 and 6525.]

UNNAMED SPECIMENS.

Besides the specimens named and described by Cope there are present in the collection many isolated bones from different parts of the skeleton which cannot be identified with certainty as belonging to any of the forms described; that they belong to some of them is practically certain. The fact that the bones are nearly always found isolated and generally in a fragmentary condition prevents any attempt at a restoration of the skeleton, but their resemblance to corresponding bones from the Texas deposits makes it probable that the animals from the two regions did not differ materially in form. One fact is noticeable, the

absence of animals of any great size as compared with the Texas forms.

Skull.— The skull is represented by two nearly perfect maxillaries, apparently the bones from the two sides of the same specimen, and several fragments showing the occipital condyles.

The premaxillaries are similar to those of *Dimetrodon* and of *Empedias* as figured by Cope. The external surface is pitted, and there was evidently a large opening of the external nares. The teeth do not show any great disparity in size nor are they chisel-shaped; there is no evidence of the presence of a diastema as in the *Pelycosauria* in general, but this may be due to the imperfection of the bone. Plate III, Figs. 2, *a* and *b*. [No. 6536.]

The occipital condyles are well rounded, hemispherical in outline, the upper edge being slightly concave, and marked by a pit near the upper edge. [No. 6537.]

Vertebræ.— There are a great many vertebræ, either isolated specimens or small lots belonging together; the majority evidently belong to one or the other of the three species of *Clepsydrops* described. There are two lots that seem different from the others.

Two vertebræ very much larger than the others apparently belong to the lumbar or posterior dorsal region. They are characterized by the breadth of the centrum as compared by its height. The lower surface is marked by a rounded but prominent keel. One shows measurements corresponding very closely with those given by Cope for *C. natalis* from Texas. It is very possible that they represent this species. [No. 6538.]

A second set of vertebræ resemble in large measure those of *Lysorhophus tricarinatus* in the free articulation of the neural arch to the centrum and the general form of the centrum; they differ, however, in the absence of the strongly marked keels and the deeply incised fossæ between them. They vary greatly in size, some being as large as those of *L. tricarinatus* and others three or four times as large. If it were not for the presence of vertebræ of different size they might be regarded as dorsals of the described species. As it is, they seem to indicate a possible new species.

MEASUREMENTS.

"Length of a centrum	.011[m]
Breadth of a centrum	.011
Length of a second centrum	.007
Breadth of a second centrum	.006 "

Plate II, Fig. 13, *a*, *b*, and *c*. [No. 6529.]

Scapula.— There are many incomplete scapulæ in the collection. They are all of small size, but resemble in form those figured by Cope (Proc. Am.

Phil. Soc., Aug. 1884, and Proc. Am. Assoc. and Sc., 1884, Vol. XXXIII), and Case (Trans. Am. Phil. Soc., 1899, Vol. XX.) One specimen shows the proximal end with articular cavity for the humerus formed by the scapula and coracoid. The scapula is perforated by a foramen just above the articular face. Plate III, Fig. 3. [No. 6540.]

Humeri.—There are four types of humerus. One, the largest, is relatively much shorter and stouter than the others, and is remarkable for the strong articular faces and the generally robust character. The proximal end is marked by prominent rugosities and the deltoid crest is laterally expanded, much more so than in the other forms, and very rough. Length .14^{m}; width of the head at the deltoid ridge .057^{m}. Plate III, Fig. 4, *a*, *b*. [No. 6541.

The second form has a much longer shaft than the first, and at all points shows a greater elegance of form at the expense of strength, but the extremities are as well formed and the articulate surfaces as distinct. This probably belongs to one of the described forms of *Clepsydrops* from Illinois, probably the largest, *C. pedunculatus*. A smaller form of the same type is represented by the distal end of another humerus, which is perfectly preserved. The entepicondylar foramen is large and elongate, the ectepicondylar foramen is represented by a notch, as in all the *Pelycosauria*; the head for the proximal end of the radius is prominent, almost hemispherical and well formed, it is continuous with the articular surface for the ulna. Height of fragment .066^{m}, width at deltoid ridge .030^{m}. Plate III, Fig. 5, *a*, *b*, *c*, and Fig. 6. [Nos. 6542, 6543, and 6575.]

The third type is represented by the distal end of a very small form similar in many respects to the foregoing, but with the internal process rounded and truncated and the entepicondylar foramen missing. The form is very small and the shaft of the bone was slender, but the distal extremity shows a strong development. The process forming the ectepicondylar notch is prominent, and the portion of the distal extremity on either side of the articular surface extended below the surface instead of lying in a line with it or not reaching so far. This form may be the same as the "No. 6" mentioned by Cope in his first contribution to the fauna of the Texas Permian, but as it was not described nor figured, it is impossible to say definitely. The humerus "No. 6" is regared by Cope as belonging to a possibly fossorial animal, this may be true of the present form, but there is no vertabræ in the collection which could go with such a type. Plate III, Fig. 7. [No. 6544.]

The fourth and last type differs very considerably from the others. The ends are concave, as if they had been cartilaginous in life, and there are no articular surfaces distinguished. The extremities are at right angles to each other, and there is a small deltoid process, continuous with the proximal end. The entepicondylar foramen is present, but there is no trace of an

ectepicondylar notch. Length .038^{m}, width proximal end .0105^{m}, distal end .0205^{m}. Plate III, Fig. 8, *a*, *b*, *c*, *d*. [No. 6545.]

Ulnæ.— There are two types of ulna distinguished by the size only. One is nearly as large as the ulna of *Dimetrodon incisivus* and quite similar to it; the proximal end only is preserved; the other is smaller, represented by the proximal end also, and probably belongs to one of the smaller species of *Clepsydrops*. Plate III, Fig. 9. [Nos. 6546 and 6547.]

Femoræ.— The femora are mostly of the same type, but show considerable variation in size. They all have the distal articular surfaces upon the inner or lower face of the distal end, showing that the leg was habitually flexed and the animal progressed, probably, with the belly on or near the ground, in the manner of the alligator. One of the medium sized forms is figured (No. 6548). Length of one specimen, .077^{m}; a larger specimen, .107^{m}. Plate IV, Fig. 1, *a* and *b*. [Nos. 6548, 6549, 6550, 6551, 6552, and 6553.]

The distal ends of two very small femora are present; they lack well-developed articular surfaces, though the contour of the extremity is the same as in the larger specimens. It seems probable that they are immature forms. [No. 6552.]

Tibia.— There is one complete tibia, somewhat crushed, and the proximal end of another. The whole bone is larger at the proximal than at the distal extremity, and is considerably curved. The shaft is more or less flattened. The proximal end has two faces, which are distinct, or nearly so; they are oblong and lie with their long axes nearly at right angles to each other. The anterior extremity of one anticular face forms the upper portion of the cnemial crest. Measurements: length, .049^{m}. Plate IV, Fig. 2, *a* and *b*. [No. 6555.]

Fibula.—What appears to be a fibula is .053^{m} long. It is a slender bone, expanded at the extremities and quite strongly curved. Plate IV, Fig. 3. [No. 6554.]

Ilia.— There are two types of ilia of about the same size. Each presents two articular faces at the distal portion for articulation with the ischium and pubis and a rather deeper articular portion of the acetabulum; at the upper portion of the acetabulum there is a prominent overhanging process. The two forms differ principally in the anterior process of the ilium with which it is attached to the sacral vertebræ. In one form it extends almost straight forward (No. 6556) and in the other (No. 6557) it is curved and the anterior end is somewhat lower than the posterior. The inner side of each presents strong longitudinal ridges and there does not seem to be any articular facet for the vertebræ. In an incomplete fragment, in which the ischium and ilium are in contact, the acetabulum is seen to be quite deep. Plate IV, Figs. 4 and 5. [Nos. 6556, 6557, and 6558.]

Footbones.—There is a large series of footbones, the position of most of which it is impossible to determine. They are all well formed, with good articular surfaces, showing that the carpus and tarsus was fairly strong and well knit. Some of the more common bones of indefinite position are shown in Plate V, Figs. 18, *a* and *b*; 19, *a* and *b*; 20, *a* and *b*. [No. 6559.]

Astragali.—There seem to be two forms of astragalus. The first is much the more slender and smaller. There are two distinct facets for articulation with the calcaneum; the upper of these is the largest and is separated from the lower by a notch which, in combination with a similar notch separating the two articular faces on the calcaneum, forms a foramen between the bones. On the opposite side of the bone there is a large face set at an angle with the body of the bone, apparently for the tibia. The lower rim of the bone between the described regions has a narrow face for the bones of the tarsus. This ilium was ascribed by Cope to *clepsydrops colletii*. The form of the bone is shown in Plate IV, Fig. 7, *a*, *b*, *c*, *d*. [No. 6560.]

The second type is of stouter proportions than the first and larger; the articular faces are arranged much the same, but are broader and the face for the distal end of the tibia is more sharply divided into faces meeting at a considerable angle. Plate IV, Fig. 8, *a* and *b*. [No. 6561.]

Neither of these forms corresponds with the figure of the astragalus of *Clepsydrops leptocephalus*, published by Cope (Proc. Am. Phil. Soc., Aug. 1884; Am. Assoc. Ad. Sc. Vol. XXXIII, 1884), nor to an astragalus of *Pariotichus incisivus* in the collection of the Walker Museum.

The strong angulation of the tibial face is described by Cope as belonging to the genus *Dimetrodon*, so that it is possible that the larger astragalus in the Illinois material may represent that genus.

Calcanea.—The calcanea are of the type characteristic of most of the Permian reptiles from America. Large, subround disks of no great thickness; the side toward the astragalus presents two facets separated by a notch; above and below are facets for the fibula (?) and the tarsal bones. Plate IV, Fig. 9, *a* and *b*. [No. 6562.]

Metacarpals and Tarsals.—The metacarpals and tarsals are long and slender, with well developed articular faces. Plate V, Figs. 1 and 2. [No. 6563.]

Phalanges.—The phalanges show the same well developed form as the preceding row, even to the terminal series. The terminal series are slender, pointed, and curved, and evidently supported strong claws. Plate V, Figs. 3–9, and 10, *a* and *b*. [Nos. 6564 and 6565.]

Among the specimens that cannot be referred with certainty to any form are the following:

Teeth.—There are several isolated teeth or portions of jaws with teeth attached, which cannot be assigned to any of the described forms. It is probable that if more complete material were at hand they would be found to belong to forms already described, either from Illinois or Texas.

"*Species one*" Cope, 1877, Proc. Am. Phil. Soc., p. 56.

This is an incomplete maxillary with six broken teeth. "They stand in close juxtaposition and are of equal size. The basal half or more of the crown displays the character of deep inflections or grooves. These teeth belong to some sauroid fish or batrachian." Plate V, Fig. 12. [No. 6566.]

"*Species two*" Cope, 1877, Proc. Am. Phil. Soc., p. 56.

A fragment of a mandibular ramus with four teeth. "The anterior of these is larger and is separated from the others by an edentulous space. Their crowns are rather elongate and are compressed, having cutting edges fore and aft. Both edges contract to the apex, but the anterior the more so. There are a few shallow grooves at the base, but they appear to be superficial only." As remarked by Cope, it is impossible to tell whether they belong to an amphibian or a reptile. Plate V, Fig. 11. [No. 6567.]

"*Species three*" Cope, 1877, Proc. Am. Phil. Soc., p. 56.

"Two stout, slightly flattened, conic teeth, without cutting edges, represent this species. They are anchylosed to a very thin plate of bone, a part of which adheres to each. The base is oblique, expanding more in one direction than in another. The greater part of the crown is marked by closely placed parallel grooves, which are more numerous than in the species No. 1. They are larger than those of No. 2, measuring .004^{m} in diameter at the base. They may belong to any one of a number of known genera of batrachia or sauroid fishes." [No. 6568.]

Besides these, there are two teeth that seem to indicate forms not otherwise represented in the collection. The first is rather conical and recurved, the upper end truncate, but the inner side shows a concave region of wear against the opposed tooth. This would seem to show that it is either an incisor or one of the lateral teeth, probably the first, of some member of the *Diadectidæ*. Plate V, Fig. 23, *a* and *b*. [No. 6569.]

The second is a very stout, conical tooth, much larger than any other in the collection. Its surface is marked with deep, irregularly arranged grooves. Plate V, Fig. 24. [No. 6570.]

A lower jaw, nearly complete, resembles very closely that of *Pariotichus* from Texas. The articular region is complete and shows a well formed face and a prominent spur extending posterior to the cotylus. Fragments of other jaws show the same feature. The outer side is marked by strong reticulate sculpture, which at the posterior part seems to radiate from a point on

the lower margin about an inch from the posterior end; on the anterior portions the lines are straighter and lie parallel to the length of the jaw. The teeth were very small. A small fragment attached to the inner side of it is covered with many minute teeth; this may be a portion of the dentition of the upper jaw. [No. 6571.]

A collection of fragments showing a fine sculpture on one side are probably portions of the skull of *Diplocaulus*. Among these are imperfect plates with a much coarser sculpture, which are probably abdominal scales. [No. 6572.]

There are two pubes nearly complete; they may belong to *Cricotus*. There is a considerable portion of the acetabular face present. This portion of the bone is thickened, and besides supporting the acetabular face has a broad face for the ilium. Just below these faces the bone is perforated by a foramen. Beneath the foramen is the symphasial region, which is remarkably broad and thick in proportion to the rest of the bone. In general the outline of the bone was subround, but the lower posterior portion was very thin, and portions have been broken away in both specimens. On the upper margin, posterior to the facet for the ilium, there is a slender tubercle which bears an articular facet; in one specimen this is isolated and in the other it is confluent with a broad facet on the thickened posterior border. Plate IV. Figs. 6, *a* and *b*. [No. 6573.]

There are a few coprolites of small size. They show spiral markings indicative of a spiral vale in the stomach of the form to which they belonged. [No. 6574.]

EXPLANATION OF PLATES.

PLATE I.

FIG. 1. *Janassa linguæformis*. Twice nat size. *a*) from below, *b*) from above, *c*) from the side.

FIG. 2. *Janassa gurleyna*. Twice nat. size. *a*) from below, *b*) from above, *c*) from the side.

FIG. 3. *Pleuracanthus quadraseriatus*. *a*) from the side, *b*) from the front.

FIG. 4. *P. gracilis*.

FIG. 5. *P. compressus*. *a*, *b*, *c*, and *d*.

FIG. 6. *Sagenodus vinslovii*. *a*) from below, *b*) from above.

FIG. 7. *S. vabasensis*.

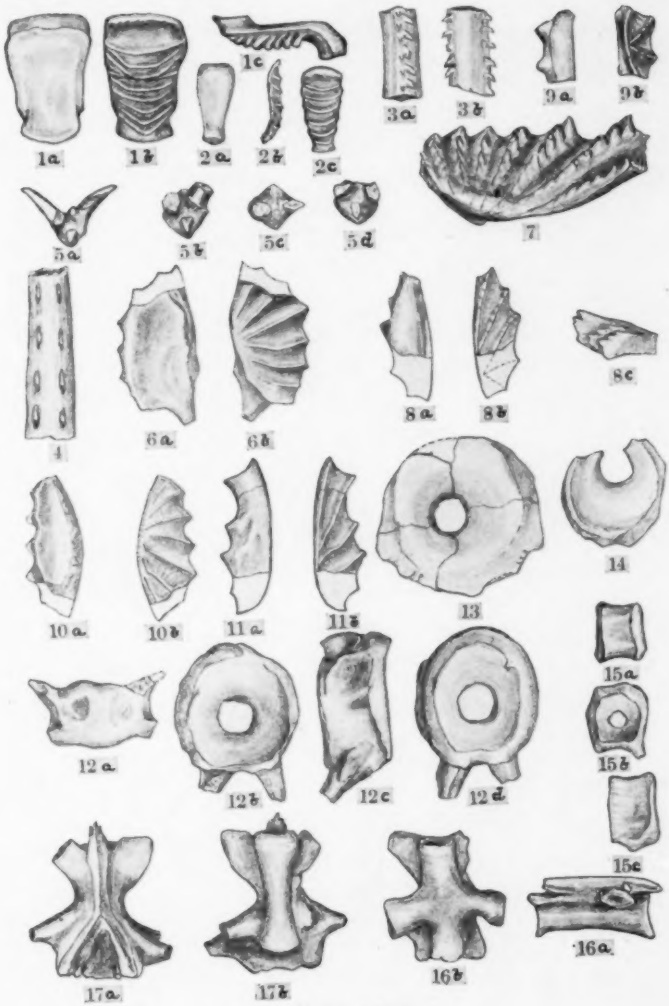
FIG. 8. *S. gurleyanus*. *a*) from below, *b*) from above, *c*) from the side.

FIG. 9. *S. pusillus*. *a*) from below, *b*) from above.

FIG. 10. *S. fossatus*. *a*) from below, *b*) from above.

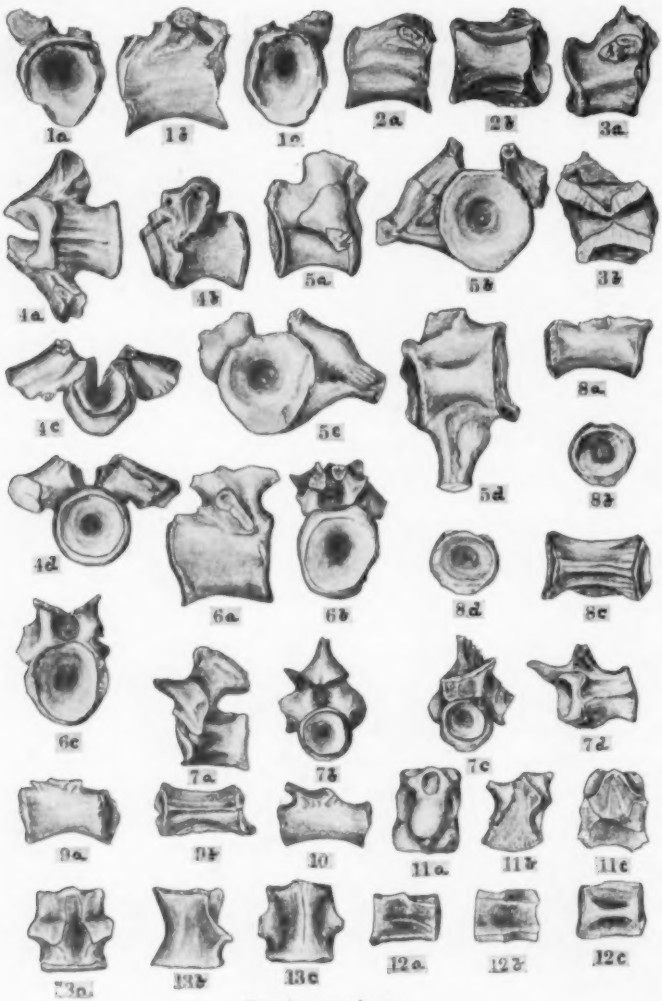
FIG. 11. *S. paucicristatus*. *a*) from below, *b*) from above.

JOUR. GEOL., Vol. VIII, No. 8 Plate I



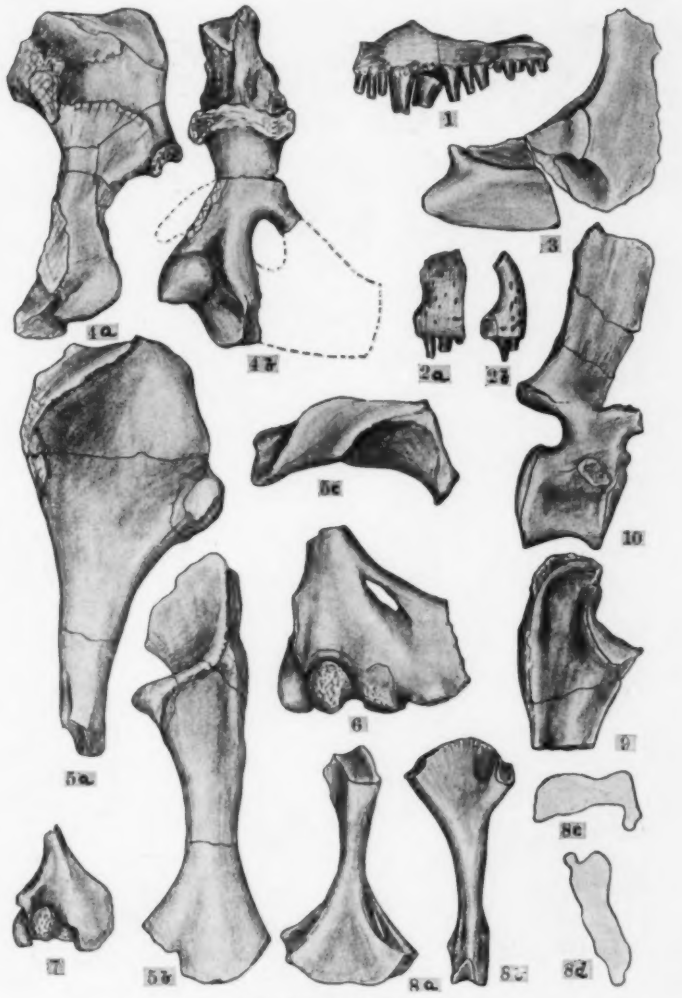
Permian vertebrates.

JOUR. GEOL., Vol. VIII, No. 8 Plate II



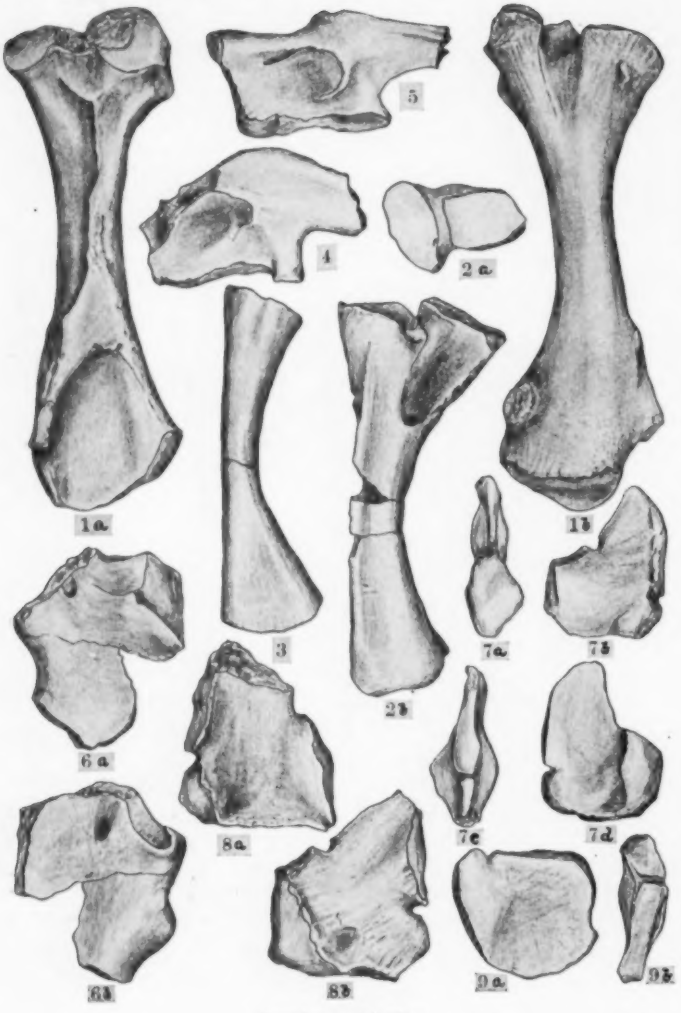
Permian vertebrates.

JOUR. GEOL., Vol. VIII, No. 8 Plate III



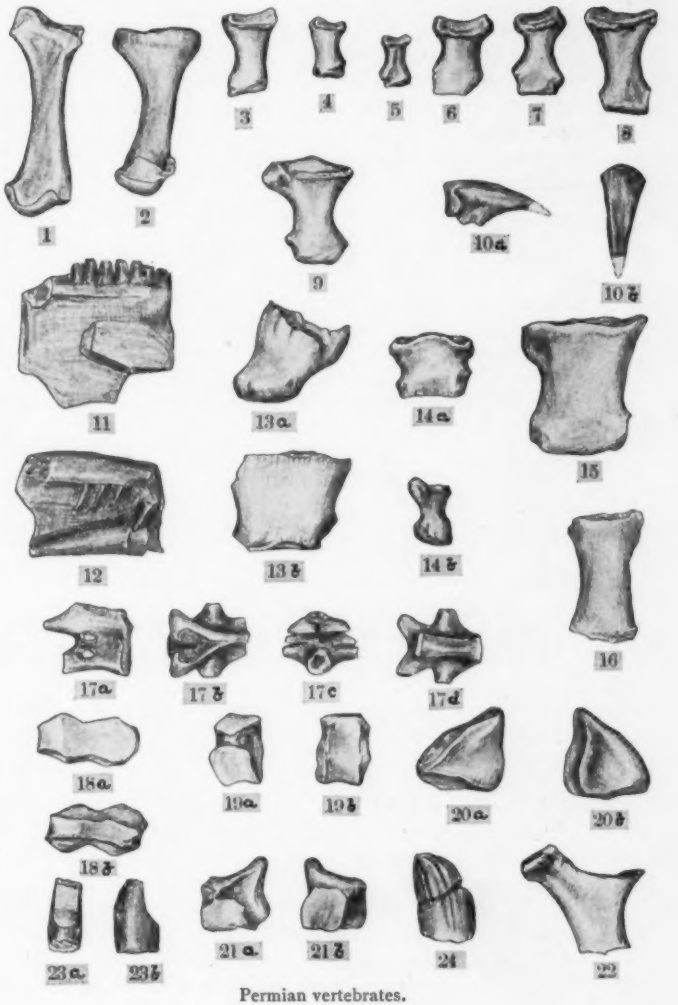
Permian vertebrates.

JOUR. GEOL., Vol. VIII, No. 8 Plate IV



Permian vertebrates.

JOUR. GEOL., Vol. VIII, No. 8 Plate V



Permian vertebrates.

FIG. 12. *Cricotus heteroclitus.* Intercentrum. *a*) from above, *b*) from before, *c*) from the side, *d*) from below.

FIG. 13. *C. heteroclitus.* Intercentrum.

FIG. 14. *C. heteroclitus.* Intercentrum.

FIG. 15. *C. gibsonii.* Intercentrum.

FIG. 16. *Diplocaulus salamandroides* Dorsal vertebra. *a*) from the side, *b*) from below. Twice nat. size.

FIG. 17. *D. salamandroides.* Dorsal vertebra. *a*) from above, *b*) from below. Twice nat. size.

PLATE II.

FIG. 1. *Clepsydrops colletii.* Dorsal vertebra. *a*) anterior, *b*) lateral, *c*) posterior.

FIG. 2. *C. colletii.* Dorsal vertebra. *a*) lateral, *b*) inferior.

FIG. 3. *C. colletii.* Dorsal vertebra. *a*) lateral, *b*) showing vertebra divided on median line.

FIG. 4. (?) *C. colletii.* *a*) inferior, *b*) lateral, *c*) anterior, *d*) posterior.

FIG. 5. *C. pedunculatus.* Anterior caudal. *a*) lateral, *b*) anterior, *c*) posterior, *d*) inferior.

FIG. 6. *C. sp.* Dorsal vertebra. *a*) lateral, *b*) posterior, *c*) anterior.

FIG. 7. *C. vinslovii.* Dorsal vertebræ. *a*) lateral, *b*) posterior, *c*) anterior, *d*) inferior.

FIG. 8. *C. sp.* Caudal vertebra. *a*) lateral, *b*) anterior, *c*) inferior, *d*) posterior.

FIG. 9. *C. sp.* Caudal vertebra. *a*) lateral, *b*) inferior.

FIG. 10. *C. sp.* Caudal verebra, lateral.

FIG. 11. *C. sp.* Axis. *a*) anterior, *b*) lateral, *c*) inferior.

FIG. 12. *Lysorhophus tricarinatus.* Dorsal (?) vertebræ. *a*) from the side, *b*) from above, *c*) from below.

FIG. 13. *L. sp.* Dorsal (?) vertebræ. *a*) from above, *b*) from the side, *c*) from below.

PLATE III.

FIG. 1. *Archeobolus vellicatus.* Maxillary.

FIG. 2. Premaxillary. *a*) from before, *b*) from the side.

FIG. 3. Scapula and Coracoid.

FIG. 4. Humerus. × ½. *a*) lateral view, *b*) posterior view.

FIG. 5. Humerus. *a*) anterior, *b*) proximal end, *c*) lateral, half nat. size.

FIG. 6. Humerus. Distal end of same form as 5.

FIG. 7. Humerus. Distal end.

FIG. 8. Humerus. *a*) anterior view, *b*) lateral, *c*) and *d*) outlines of the proximal and distal faces in natural position.

FIG. 9. Proximal end of Ulna.

PLATE IV.

FIG. 1. Femur. *a*) anterior, *b*) posterior.

FIG. 2. Tibia. *a*) proximal end, *b*) anterior view.

FIG. 3. Fibula.

FIG. 4. Ilium.

FIG. 5. Another type of ilium.

FIG. 6. Pubis. *a*) inner view, *b*) outer view.

FIG. 7. Astragalus of *Clepsydrops sp.* *a*) tibial face, *b*) anterior (?) face, *c*) calcaneal face, *d*) posterior (?) face.

FIG. 8. Astragalus of *Clepsydrops sp.* *a*) anterior (?) face, *b*) posterior (?) face.

FIG. 9. Calcaneum. *b*) astragalus face.

PLATE V.

FIGS. 1 and 2. Metacarpals of *Clepsydrops.*

FIGS. 3–9. Phalanges of *Clepsydrops.*

FIG. 10. Terminal phalanx of *C.* *a*) lateral, *b*) superior views.

FIG. 11. "Species one."

FIG. 12. "Species two."

FIG. 13. Phalanges of *Cricotus.* *a*) lateral, *b*) anterior views.

FIG. 14. Phalanges of *Cricotus.* *a*) anterior, *b*) lateral views.

FIGS. 15 and 16. Phalanges of *Cricotus.*

FIG. 17. *Diplocaulus salamandroides.* Dorsal vertebra. *a*) lateral, *b*) superior, *c*) terminal, *d*) inferior views.

FIGS 18–21. Carpal bones.

FIG. 22. Proximal end of a rib

FIG. 23. Incisor tooth. *a*) anterior view, *b*) lateral.

FIG. 24. Tooth.

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SOME PRINCIPLES CONTROLLING THE DEPOSITION OF ORES.[1]

I WOULD hardly have ventured to talk on the subject of ore deposits to you if I had not approached the subject from a different point of view from the majority of men who have considered it. The point of view from which the subject of ore deposits has been most frequently considered has been that of a study of ore deposits themselves. A geologist or mining engineer has studied this or that ore deposit, or a number of ore deposits in different districts, and has then generalized concerning the ore deposits of other districts, and perhaps of the world. I also have considered the subject of ore deposits to some extent from that point of view, but if I had done this only, I would not have ventured to give a general address upon the subject.

Some years ago I took up the question of the alterations of rocks — the alterations of all rocks by all processes. In treating this subject it became necessary for me to consider somewhat fully underground water; the principles which control its flow; the manner in which it works; the results which it accomplishes. After I had reached certain conclusions upon that subject it seemed to me that the deposition of most ores was a special case falling under the general principles controlling the work of underground water. Therefore it is from the point of view of the circulation and work of underground water that I wish to consider the subject of ore deposits tonight. However, I cannot go into the subject fully, and will be obliged to ask those of you who are especially interested in it to refer to my more

[1] An address presented to the Western Society of Engineers at Chicago, June 13, 1900. The address is also printed in the journal of that society for December 1900.

This paper covers the same ground as a paper on the same subject, in a somewhat different form, which has already been published in the Transactions of the American Institute of Mining Engineers. Vol. XXX, 1900, pp. 1–151.

extended paper found in Vol. XXX of the *Transactions of the American Institute of Mining Engineers.*

There are three great classes of ore deposits; (1) those which are produced by igneous processes; (2) those which are produced by the direct processes of sedimentation; (3) those which are produced by the work of underground water. The last class is by far the largest, and it is the only one which I shall consider this evening.

My first, then, and my fundamental premise is, *That the most important class of ore deposits is the result of the work of underground water.* This premise I shall not attempt to prove; but because it is accepted by most geologists and by most mining engineers shall use it as a starting point.

My second fundamental premise is, *Ore deposits are derived from the outer crust of the earth, from that part of the crust of the earth which I have called the zone of fracture.*[1] There has been much discussion as to whether ore deposits are produced by descending waters, lateral-moving waters, or ascending waters. One of the most comprehensive papers which has been presented upon this subject was by Posepny.[2] In this paper Posepny holds that the original source of the metals of practically all the ore deposits of the class produced by underground water is the Barysphere (heavy-sphere), and therefore that the metals come from very far below the surface of the earth. The water in some mysterious way came from this heavy sphere, presumably very deep seated. The water rising from the Barysphere, where the rocks are supposed by some to contain more metalliferous material than near the surface, brought the metals of the ore deposits to their present positions. This view has been presented at great length by Posepny, ably argued, and he has had many disciples. Now it seems to me that the well-established principles of physics absolutely disprove this

[1] Principles of North American pre-Cambrian Geology, by C. R. VAN HISE: Sixteenth Ann. Rept. U. S. Geol. Surv., 1894–5, Pt. I, p. 589.

[2] The Genesis of the Ore Deposits, by F. POSEPNY: Trans. Am. Inst. Min. Engineers, Vol. XXIII, 1894, pp. 197–369.

hypothesis; and it further seems to me that observed geological phenomena also disprove it.

I have elsewhere divided the outer crust of the earth into zones, in descending order as follows: a zone of fracture, a zone of combined fracture and flowage, and a zone of flowage.[1]

Now, we will suppose that the crushing strength of the strongest rock is such that at a depth of twenty thousand meters below the surface the weight of the superincumbent rock (less the floating effect of underground water) is as great as the crushing strength of the rock. We will suppose that such a rock as the Berlin granite of Wisconsin, the strongest rock yet tested, having a crushing strength of 47,674 pounds per square inch,[2] extends from the surface to an indefinite depth. We will further suppose that in some way openings of some kind, say large cracks, are produced at the depth where the rock is under weight as great as its crushing strength. What would happen? You engineers know very well the rock would be crushed and the openings would close. Therefore at a depth of more than 20,000 meters below the surface of the earth, where the weight of the superincumbent rock is greater than the strongest rocks, if it be supposed that cracks of a considerable size could be formed, the pressure would crush the rocks and close the cracks. But the crushing strength of the great majority of the strong rocks does not exceed one half that of the Berlin granite. Moreover rocks at considerable depth are at higher temperatures than normal, and this probably weakens them. Consequently upon physical grounds we are prohibited from supposing that there are cracks and crevices of considerable size at more than a very moderate distance below the surface of the earth. But this conclusion does not rest upon physical principles alone. I have shown that there is another way besides crushing by which

[1] Principles of North American pre-Cambrian Geology, by C. R. VAN HISE: Sixteenth Ann. Rept. U. S. Geol. Surv., 1894–5, Pt. I, p. 589.

[2] Building and Ornamental Stones of Wisconsin, by E. R. BUCKLEY: Bull. Wis. Geol. and Nat. Hist. Surv., No. 4, 1898, p. 390.

rocks are readjusted to deforming stresses.[1] If the movement be slow and the temperature that of moderate depth the stress does not need to accumulate so that it shall be greater than the crushing strength of the rocks. Under such conditions, long before the crushing strength is reached, the contained water begins to act upon the material of the rocks and re-arranges it by continuous solution and deposition; so that it behaves as a plastic body. At all times the rock is a solid except for the infinitesimal amount held in solution; and yet it continually adjusts itself to the deforming stresses. A great many rocks which have been thus deformed under deep-seated conditions have a laminar structure which is analogous, not exactly similar, but analogous, to the leaves of a book. To make the analogy exact it would be necessary to suppose that the leaves are welded together, *i. e.*, held firmly by the molecular attractions between them. What has happened in the case of these laminar rocks? They have been transformed from a massive to a laminated form by recrystallization, but in many cases combined with mineral granulation and differential movements of the mineral particles. During the process of recrystallization, for each mineral particle, material is continually taken into solution on the sides where subjected to greatest stress and deposited on the edges where the stress is less, until the laminar structure is produced. The process of adjustment largely and in many instances mainly by continual solution and redeposition is rock flowage. Now rocks in which this process has taken place are found at the surface at many places. Moreover these rocks are frequently those of great strength. In many places it is certain that the amount of material which has been removed by erosion since the rocks were recrystallized is not more than 2000 or at most 3000 meters. Since, therefore, the process of rock flowage often takes place at much less depth than that at which rocks are crushed, it follows that large openings are not likely to exist at depths so great as above calculated for the closing of openings

[1] Metamorphism of Rocks and Rock Flowage, by C. R. VAN HISE: Bull. Geol. Soc. Am., Vol. IX, pp. 269–328, Pl. XIX.

by crushing. It is highly probable that few openings of appreciable magnitude exist at depths so great as 10,000 meters.

Therefore from the principles of physics and from observation we conclude that crevices and cracks of considerable magnitude do not exist below a very moderate depth. I would not say that minute cavities filled with liquid do not exist in the zone of rock flowage; I would not say that very small openings filled with gases may not exist in that zone; but there is every reason to believe that such cavities are exceedingly small. And it is well known that ore deposits in order to be of economic value must be of considerable magnitude. Such deposits were not formed in the minute and discontinuous openings filled with gas or liquid which very possibly exist at great depth.

But let us now consider this subject from another point of view. You as engineers know very well that the friction of a moving liquid increases very rapidly as the size of the passage through which it moves decreases. This is true even of super-capillary tubes. It is still more true of capillary openings, and the resistance goes up very rapidly as the capillary tubes decrease in size. When the openings become so small that the molecular attractions extend from wall to wall or the openings are sub-capillary, the resistance is so great that the flowage is practically nil.[1] Now it is perfectly evident that a deposit of mineral material in an opening is not the work simply of the water that occupied it at any one time. Ordinarily, underground solutions of silica do not contain upon the average more than one part of silica per 100,000 parts of water, so that if an opening be filled with quartz, the most abundant of all the gangue minerals, we must suppose at least 100,000 times as much water went through the opening as there was quartz deposited. Therefore it is perfectly clear that the material for large ore deposits can only be gathered and the ores deposited in the zone where there is a vigorous circulation, and vigorous circulation is

[1] Metamorphism of Rocks and Rock Flowage, by C. R. VAN HISE: Bull. Geol. Soc. Am., Vol. IX, p. 272.

impossible in the deep-seated zone in which there are no continuous cracks and crevices of considerable size; hence the hypothesis of the derivation of the metals of the ores from the Barysphere is untenable. Valuable ore bodies have been deposited in openings and passages of considerable size and by a vigorous underground circulation. Since the magnitude of openings and vigorous circulation are correlative with, and exist only in the upper zone, that of fracture, the ores must have been derived from and deposited in this upper part of the crust of the earth.

If, then, we admit the fundamental premise, that the majority of ore deposits are the work of underground water, it seems to me that the conclusion cannot be escaped that the metals which are in the ore deposits are immediately derived from an upper zone, probably having a maximum depth of 10,000 meters, or seven or eight miles, in which the circulating waters are vigorous and effective.

However, I do not assert that now, or at any time in the past, metals for ores have not been derived ultimately from a deeper source through the agency of vulcanism, the medium of transfer being the igneous rocks. We do not know how deep down the igneous rocks which are intruded into the zone of fracture or flow out at the surface of the earth are transformed to magma, if they have not always existed as magma. We do not know very well the process by which the igneous rocks make their way up through the solid rocks of the zone of flowage. We do know, however, that they come from a very considerable depth, and take advantage of openings and cracks and crevices as soon as they reach the zone of fracture. For instance, in the Sierra Nevada, where there are various great sets of joints in the granite — vertical, inclined, and horizontal — the lava coming up from below has wedged itself into these joints, producing sets of parallel dikes. As these joints are utilized by the igneous rocks, so are openings of other kinds where igneous rocks intrude the zone of fracture. Igneous rocks in vast quantities as lava are poured out on the surface or as tuff fall upon it.

These igneous materials undoubtedly do in many cases bear metals out of which ores are made. But in few instances are they ores as igneous rocks. Igneous rocks so rich in iron as to serve as ores have been found on a very small scale. Vogt[1] holds that certain sulphide ores are produced directly by processes of differentiation of igneous rocks; but while I do not deny this, I also would not unqualifiedly assent to it. However this may be, there is fair agreement on the part of all that the great mass of the metals which come from the igneous rocks are derived from them through the agency of underground water, and that the ores which are now worked by man are preponderantly concentrates from the igneous rocks, or from the sedimentary rocks, or from the two combined. But if some ores have directly solidified as magma, they do not come within the scope of the discussion tonight; for I said at the outset that only ores produced by underground water would be considered. Such ores are probably derived for the most part from the upper 10,000 meters of the crust of the earth.

My third premise follows directly from the considerations already given: *If the waters below the zone of fracture do not circulate vigorously, and if vigorous circulation by underground water be necessary in order that ore deposits be produced, it follows that the waters which perform this work are of meteoric origin.* They are the waters which fall from the clouds upon the earth and sink into it. I do not deny that some small part of water concerned in the production of ores may be derived from below the zone of fracture; I do not deny that the igneous rocks rising from below bring with them small amounts of water; but these amounts are insignificant — are inappreciable in quantity as compared with the vast amount of water which is necessary to do the work of ore deposition. We know to a certainty that the great mass of underground circulating waters are of meteoric origin. For instance, if a well be drilled at Chicago through the limestones and shales near the surface

[1] J. H. L. VOGT: Zeitschr, für prakt. Geol., January and April 1893, October 1894, April, September, November, December 1895.

into the sandstone below you know that great quantities of water issue. The water falls upon the ground far to the northwest in central Wisconsin, where the sandstone reaches the surface. It follows this pervious formation below impervious strata, and when the impervious strata are punctured at Chicago rises to the surface through the opening. So it is with artesian wells everywhere. I repeat, *The waters which we know to be vigorously circulating are of meteoric origin, and these are the waters which have deposited the ores.*

We are now ready to pass to the fourth of my premises, viz., *The movement of underground water is mainly due to gravitative stress.* This is perhaps so plain to you as engineers that it will hardly need proving; but certainly many men who have written about ore deposits have given other explanations. Why does the water rise in the artesian wells in Chicago? Simply because the level of underground water at the northwest where the sandstone is fed is at a higher elevation. The difference in elevation is only a few hundred feet; and yet the difference in the weight of the columns, or the force of gravity, is sufficient to drive the water underground through the sandstone for a hundred or more miles to Chicago and make it rise considerably above the level of Lake Michigan. If the deformation had been such that the porous formation had somewhere been depressed nearly to the bottom of the zone of fracture, and the openings did not thereby become smaller, this in no way would have lessened the speed of circulation. It is therefore clear from our knowledge of artesian wells that a very moderate head is entirely adequate to account for an underground lateral circulation of great length and for a vertical circulation of great depth—entirely adequate to account for it. If this be true, why should we appeal to subterranean heat or to the unknown mysterious forces at the depths as a main cause for underground circulation?

I do not deny that in some cases water is squeezed out of the rocks by orogenic movements, nor do I deny that heat produces an effect in underground circulation. We may suppose,

for instance, that the water entering at one point issues at another point at the same elevation, after following a deep underground path. Suppose the water during the journey comes in contact with volcanic rocks, or suppose the water becomes warmer as the result of the normal increase in temperature with increased depth. We will suppose, for the sake of simplicity, that the temperature of the water is 0° C. where it enters the ground, and at a temperature of 100° C. where it issues. This is an extreme case, and beyond the facts; but it makes the illustration simple. During its journey the water expands as a result of its rise in temperature, and a unit volume of the issuing water weighs only about 96 per cent. as much as does a unit volume the entering water. The cooler or descending column contains a greater mass of water than the ascending column; it is, therefore, pulled stronger by the force of gravity; and consequently circulation takes place. The descending column falls and the ascending column rises because of the gravitative stress.

In the case of the Chicago artesian wells we have seen that the flowage is due to differential gravitative stress resulting from difference in elevation. In the case we have just considered, we have seen that the flowage is due to differential gravitative stress occasioned by difference in temperature. Therefore, underground water circulation caused by gravitative stress may be initiated by difference in head or difference in temperature, or by both combined. Ordinarily difference in head and difference in temperature work together. Commonly water enters the ground at a higher level than it issues; and I think it can be shown that water which is descending is, upon the average, at a lower temperature than water which is ascending, although I cannot stop to fully discuss this point. Therefore the descending column is heavier. Hence, unequal gravitative stress, caused by difference in head and by difference in temperature, is the adequate cause to which I appeal to account for the circulation of underground water which does multifarious kinds of geological work, a small part of which is the deposition of ores.

It is now necessary to consider in some detail the manner in which underground water moves. For a long time I have realized that if underground water had a difference in head that it might penetrate to a great depth and rise again to the surface;

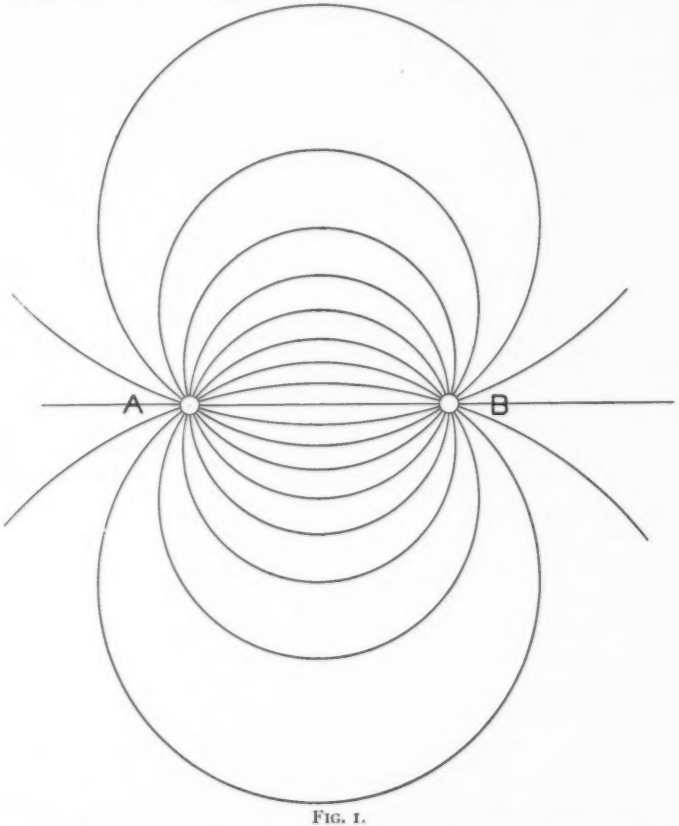

FIG. 1.

but I did not realize that it was not necessary to assume exceptional openings for such a circulation. I assumed that where such a circulation took place exceptionally favorable channels were available; but a recent paper by Professor Slichter[1]

[1] Theoretical Investigation of the Motion of Groundwaters, by C. S. SLICHTER, Nineteenth Ann. Rept. U. S. Geol. Surv., 1899, Pt. II, pp. 295–384.

upon the motion of groundwaters showed me that this was an entirely unnecessary assumption, and gave me the additional data needed upon this point. This chart (Fig. 1) is a horizontal diagram. A represents one well and B another well, separated by a homogenous porous medium. Into the well B, I pour water. In the well A there is no water at the outset; and the water flows from the well B to the well A through the medium. What is the path of the water? Its flowage is represented by the curved lines. Some of the water goes in a nearly direct course. Another part takes a somewhat curved course. Still other parts of the water follows a very indirect course, represented by the longer curved lines. All of the available cross section is utilized. If for instance this room were filled with water, and water were running in at one place in the front end of the room and were escaping at one place in the rear end of the room with equal speed, would the water simply follow the direct line between the two? You know perfectly well it would not. The entire available cross section of the room would be utilized, although the more direct course would be utilized to a greater extent than the more indirect course. This is intended to be illustrated on the chart (Fig. 1) by the lines representing the nearly direct courses being close together, and the lines representing the indirect courses being farther apart.

This chart (Fig. 1) then represents the horizontal circulation. If we pass to the vertical circulation the flowage is represented by this chart (Fig. 2). The water is being poured into the well B and passes to the well A. The water follows the course of the curved lines, so that with a difference in head equal to the difference in the level of the water in the two wells, a considerable part of the water being poured into B and passing through the homogenous porous medium to A penetrates a considerable depth, from which it rises and enters the well A. Now what will be the limit in nature of the downward search of underground water? We have already given it. Manifestly the lowest limit of effective circulation at any place is the bottom of the zone of fracture at that place. The zone of flowage

below is practically impervious. However, an impervious limiting stratum may exist at depths far less than the bottom of the zone of fracture. An impervious limiting stratum, perhaps a shale, may be found at a depth of 100 meters or less, or at any

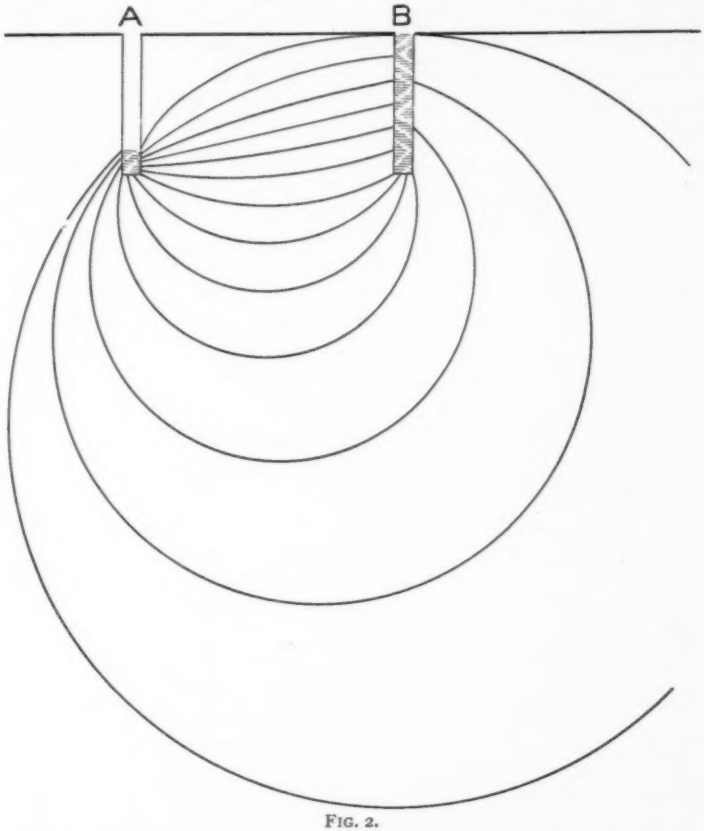

FIG. 2.

depth intermediate between this and the bottom of the zone of fracture for the strongest rocks. Where there are one or more pervious strata which are inclined and above, below, and between which are impervious formations, there may be two or more

nearly independent circulations. To illustrate, at Chicago the St. Peter's sandstone, the Potsdam sandstone, and even different parts of the Potsdam sandstone have more or less independent circulations. If a limiting stratum be supposed to be half-way down on the chart (Fig. 2) the lines of flow above this stratum would not be as they are now, but would be flatter and would be limited by the impervious rock.

Under natural conditions wherever there is an impervious rock there is a limit of some particular circulation in that direction. A limiting stratum may therefore be very near the surface, at the bottom of the zone of fracture, or at any intermediate depth; and theoretically a moderate head is sufficient to do the work of driving the water to any of these depths. Indeed, there is no escape from the conclusion that at least some circulation does occur in the deeper parts of the zone of fracture with a very moderate head. Of course in proportion as the head is great the circulation at depth is likely to be vigorous. But it may be objected that a deep circulation, while theoretically possible, must be exceedingly small in quantity, and consequently of comparatively little account in the deposition of ores. But the consideration of the underground circulation in reference to the Chicago artesian wells, shows that this objection has little weight. (See p. 737.) Moreover, the deeply circulating water, if less in quantity than that near the surface, takes a longer journey and is longer in contact with the rocks through which it is searching for the metals. Not only so, but it is at a higher temperature than the water at higher levels; and this also is favorable to taking mineral material in solution. And, finally, because it has a higher temperature it has less viscosity. While the variable viscosity of water is not so very important in reference to circuculation in super-capillary tubes, in capillary tubes, which constitute a very large fraction of underground openings, and especially those at considerable depth, the viscosity is important —the flowage increasing directly as the viscosity decreases. The viscosity of water at 90° C. is only one fifth as much as it is at 0° C.; and therefore with a given head of water in capillary

tubes, if the temperature be considerably increased—and but a moderate depth is required to give considerable increase—the water moves several times as fast as it would at the surface under conditions similar in all respects save temperature. Therefore, because of these three factors, long journey, high temperature, and low viscosity, we cannot exclude the deep circulation from consideration. This circulation is indeed believed to be very important in the deposition of ores.

We are now prepared to consider the actual journey of underground water. Where water falls upon porous ground it finds innumerable openings through which it enters and begins its underground journey. This circulating water, as far as practicable, under the law of the minimum expenditure of energy, follows the paths of easiest resistance. But these are the larger openings, because resistance due to friction along the walls and within the current is very much less per unit circulation in large than in small openings. While therefore water enters the ground at innumerable small openings, as it goes down it more and more seeks the larger openings. Once found, it holds to them. The farther it continues its journey, the greater the proportion of the water which follows the larger openings. But if this be true, the water in its descending course is more likely to be widely dispersed and in the smaller openings; and in its upward course more likely to be concentrated and in the larger openings.

We can now follow the course of underground water in detail, but in doing this it is necessary to consider the elements of the problem separately. It is only by passing from a simple case to the very complex one of nature that we can understand the latter. Here is a chart (Fig. 3) which shows the surface of a slope, the level of groundwater, and the flowage of water in the simplest imaginable case. Below the level of groundwater all the openings in the rocks, great and small, are filled with water. The rocks are saturated. In the case represented I have supposed that all of the water enters at a single point, A; and that all of it issues at a single point, B. The curved lines represent the

flowage of the water through a homogeneous porous medium. In the next chart (Fig. 4) I have supposed water to enter at three points and issue at one; and I have supposed the flowage from each point of entrance to occur just as if no water were

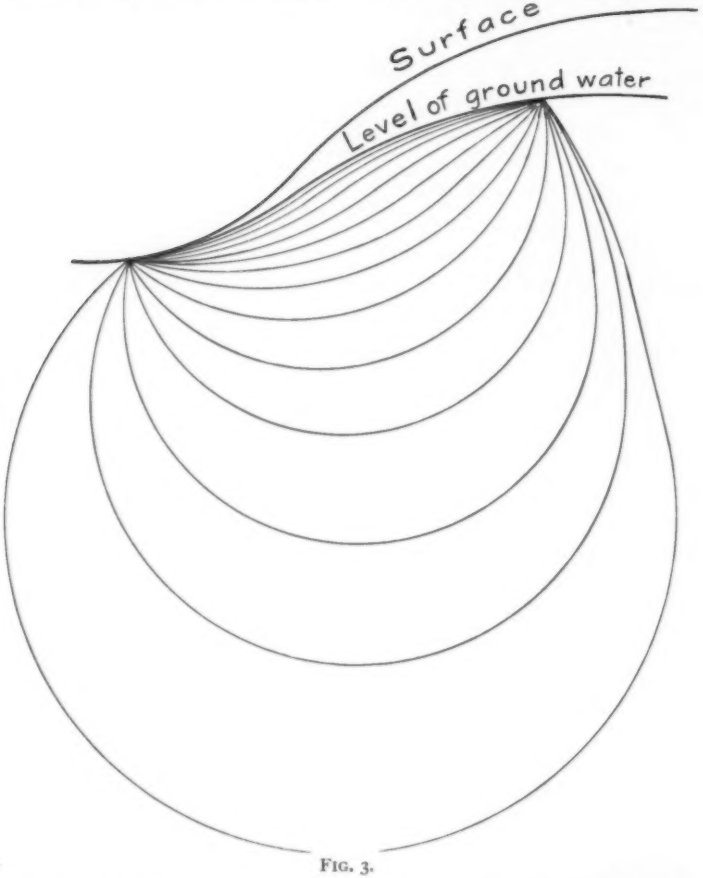

FIG. 3.

entering anywhere else, and therefore the systems of flowage to be superimposed. Of course this is not a real case. Underground water does not diverge from a single point and converge at another point in independence of the water entering

at other points. The water entering at innumerable points in vertical section and in horizontal section mutually interfere, and make the course for any given particle of water rather simple.

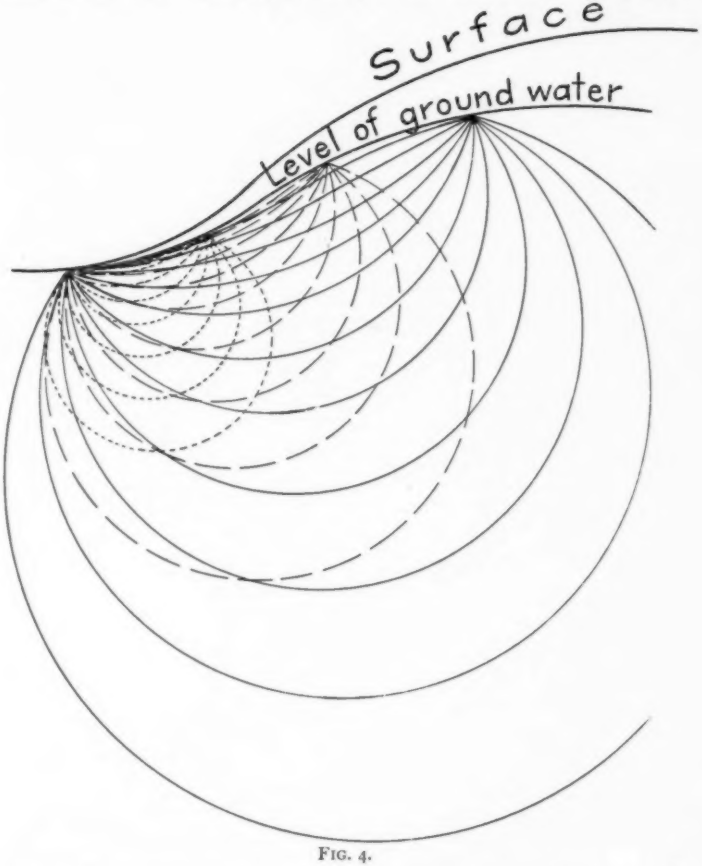

FIG. 4.

This I have tried to represent by another chart (Fig. 5). In this chart I have supposed particles of water to enter at equal horizontal intervals, and issue at a single point. You note that the water near the crest begins its journey by almost vertical

descent. In proportion as the entering water is near the valley the horizontal component becomes more important. The water near the valley follows a comparatively shallow course; but this water uses all the available space near the surface, and conse-

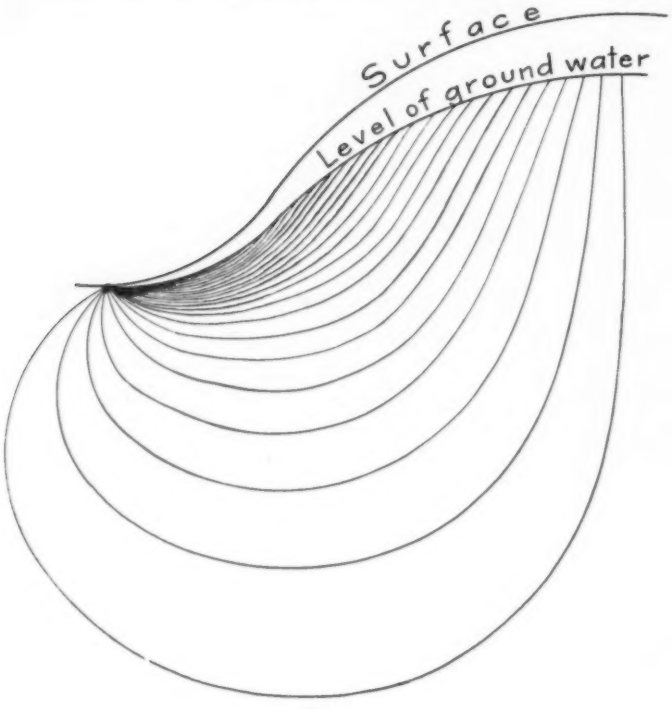

FIG. 5.

quently the water entering at the higher ground necessarily follows a long, circuitous, and deep course. The chart (Fig. 5) therefore represents the flowage with many points of entrance and a single point of exit, where there is interference of the circulating waters.

Thus far it has been supposed that the ground is uniformly porous, like an evenly grained sandstone without joint or fracture

of any kind, in which the water can go in all directions with equal ease. But absolute uniformity does not exist in nature. The openings in rocks are never of uniform size; they are never equally distributed. Suppose half way down the slope

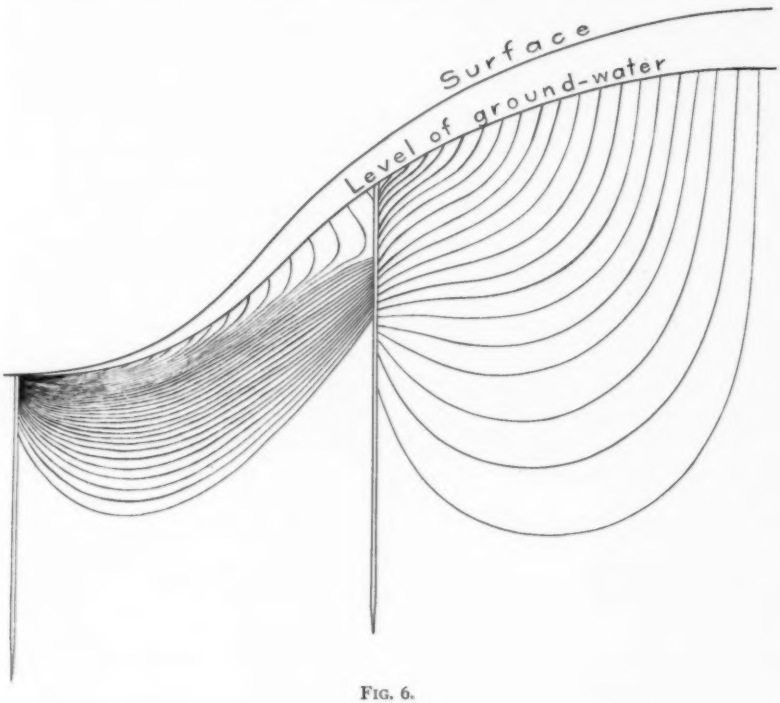

FIG. 6.

there is a vertical opening of unusual size transverse to the plane of the chart (Fig. 6), and another similar opening below the valley. If you please, we will call them fissures. These fissures, because large openings, will be fully utilized by the underground water. We readily see that groundwater will enter the higher fissure at many points and from various directions. Ordinarily it will enter the upper part while it is still descending; it will

enter the central part laterally; it will have begun its ascent before it enters the lower part. Therefore a fissure upon the middle of a slope will be very likely to receive water from above, from the side, and from below. But at a certain area of a fissure well up on the slope the water continuously received at the upper side of the fissure will escape laterally at the lower side. This water and that entering the ground below the upper fissure will make its way to the fissure below the valley. But here the level of groundwater is at the surface. Consequently all the water entering this fissure will ascend quite to the surface, and issue as a spring. If there be a fissure at the crest we can see that the descending water will go a long way down; but the waters will nowhere be ascending. If there be a fissure on the slope, both descending and ascending waters will ordinarily be active; although it is of course recognized that in fissures thus located the conditions may be such that the waters will ascend or descend only. If there be a fissure below a valley where the level of groundwater is at the surface the water will all be ascending; and there will be no descending water. At such places we have springs. Springs do not issue from the tops of mountains, but from slopes and valleys, most frequently the latter. Illustrating this are the Yellowstone Park springs of the Firehole River. The waters which feed the springs fall upon the crests and slopes of the mountains adjacent; on their way to the valley go deep below the surface, and at the Firehole ascend as hot springs and geysers. The water is driven by gravity due to a considerable head and the lower temperature of the descending column.

You are all doubtless aware that three theories are maintained as to the source of the waters which deposit ores. Some hold that the waters doing the work are descending; others that they enter laterally; others that they are ascending. The first is known as the descension, the second as the lateral secretion, and the third as the ascension theory. If my argument be correct as to a limit to the zone of fracture, fissures, as well as all other openings, must gradually become smaller and smaller,

and finally die out altogether. Water in a fissure may descend or may ascend for a considerable distance; but it is perfectly clear that, so far as fissures are concerned, except for the small amount entering the surface openings, the water must enter laterally. Consequently, if we apply the lateral-secretion theory broadly enough, we may say that all the waters which feed the fissures are lateral-secreting waters. But if we are descensionists, and consider only the upper part of a fissure on the slope—and that is what many very naturally have done because this is the part of the fissure most easily observed—we may say that the waters which are doing the work are descending waters. Or, if we are in such a district as that of the Comstock lode, in which are found great volumes of ascending water, we may say that the waters which are depositing the ores are ascending. All may be true. But in the past Sandberger held that lateral-secreting waters in the narrowest sense did all the work, and he refused to believe that ascending and descending waters were of importance; and Posepny held that ascending waters did nearly all the work, and gave small consideration to lateral-secreting and descending waters; whereas you see with perfect clearness that each theory is incomplete. Both are needed; they supplement each other.

Passing now to the work of underground water, we find there are very great differences in the nature of the work which takes place above the level of groundwater and below the level of groundwater. The first is called the belt of weathering; the second the belt of cementation[1] (see Fig. 7). Also there are great differences in the work which takes place in the zone of fracture, which includes both the belts of weathering and cementation, and that in the deep-lying zone, that of rock flowage. All of these differences have a very close bearing upon some phase of ore deposition. But the subject is too complex for me to take up fully, and I shall simply give the major differences in the reactions without stopping to demonstrate their

[1] Metamorphism of Rocks and Rock Flowage, by C. R. VAN HISE: Bull. Geol. Soc. Am., Vol. IX, p. 278.

correctness.[1] Above the level of groundwater, in the belt of weathering, the chemical reactions of oxidation, carbonation, hydration, and solution are the rule. The mechanical results are disintegration, softening, and decomposition of the rocks. Below the level of groundwater, in the belt of cementation, the chemical reactions of oxidation and carbonation are less active; but hydration occurs very extensively. Instead of solution, deposition is continually taking place. The mechanical result is that the rocks, instead of being disintegrated, softened, and decomposed, are hardened, the openings being cemented. Where comes the material for cementation? Why, from this belt of weathering

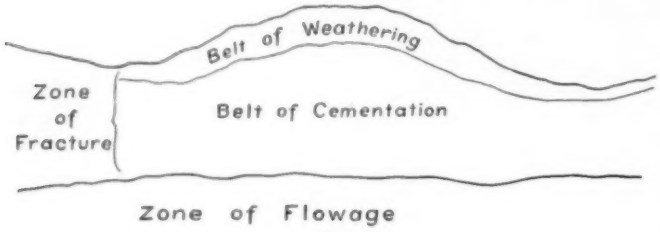

FIG. 7.

above, where solution is taking place. If the waters in the belt of weathering are continuously taking materials into solution, and are continuously depositing material below, as denudation goes on these belts steadily migrate downward. The present belt of weathering not long ago geologically was in the belt of cementation. While, therefore, the belt of weathering at any given time in the past, as now, was relatively thin, it may have moved downward for thousands of feet. In many mining districts it is estimated that from 1000 to 3000 or more meters of rock have been removed from above the present surface. All of this thickness has been in the belt of weathering; although at any one time the belt of weathering may have been but a score or few score meters in thickness. Therefore, from the belt of weathering a great and adequate amount of material may

[1] For a fuller discussion see Metamorphism, cit., pp. 277–286.

have been derived to fill the cracks and crevices of the entire belt of cementation below, although this belt may be thousands of meters thick. This process of filling cracks and crevices by deposition is the general law for the great belt of cementation below the level of groundwater, just as certainly as solution is the general law for the belt of weathering above the level of groundwater. These are the dominant processes. However, I by no means assert that deposition does not occur in the belt of weathering, and that solution does not occur in the belt of cementation. Indeed, the solution of material in various places, in both the belts of weathering and cementation, and the deposition of this same material or a part of it in the same belts at other places are very important processes.

We therefore conclude that the solution of material in the belt of weathering and the deposition of material in the belt of cementation, and the solution and deposition of material within the same belts, fills the openings in the rocks below the level of groundwater. These processes are gradually changing the soft sandstones, such as exist below the surface limestone of Chicago, into quartzite. By the same processes fractures—small and great, from minute joints to great fissures—are filled by deposition of material from underground waters. The formation of ore deposits is largely an incident of this process. The volume of material transported from the belt of weathering and deposited below in the openings of the belt of cementation, and transferred from place to place within these belts, is many million times greater than the ore deposits. The development of ores is merely an exceptional case of a widespread and most important geological process, the deposition of ores involving only a consideration of the particular materials which are of value to man. This evening I propose very briefly to discuss the source of such materials: how they are carried; why and where they are deposited. The particular case is under the general laws which control the general process of solution and deposition.

There are a great many chemical laws which affect the process of ore deposition, and a few of them I am obliged to

mention. The first law is: All the elements and compounds of nature are soluble to some extent in water. If water be placed in contact with an hundred substances, it will hold some part of every one of those substances in solution. It follows that if, in the journey of underground water, it finds here and there gold or silver or lead or zinc or iron, in quantity small or great, those materials to some extent will be taken into solution. The second law is the fundamental principle of chemical dynamics, viz.; Chemical action is proportional to the active mass. To illustrate, other things being equal, the greater the quantity of a compound present, the greater the quantity which will be taken into solution and deposited from solution.

The materials will be likely to be taken into solution in large measure during the descending course of the water; and deposited from solution in large measure during the ascending course of the water. For this there are a number of reasons. First, solution is likely to occur during descension because the conditions are those of increasing temperature and pressure. It is well known that increase of temperature greatly increases the solvent power of water. In many cases a slight rise in temperature is sufficient to increase this activity in an amazing degree; in fact out of all proportion to the increase of temperature. Deposition is likely to occur during ascension because the conditions are those of decreasing temperature and pressure.[1] Second, some substances are held in solution better than others. Certain substances, such as quartz, may be deposited during the downward course of the water, and a more soluble substance, such as gold, silver, or some other substance, be dissolved at the same time. Third, the larger openings, such as fissures, are the trunk channels of water circulation. In them the waters from different sources mingle; and this to my mind is the most important single factor—probably the dominant factor,

[1] The relations of temperature and pressure to solution and precipitation are much more complicated than implied in the above general statement. For a more nearly exact expression of the facts see Some Principles Controlling the Deposition of Ores, by C. R. Van Hise: Separate from Trans. Am. Inst. Min. Engineers, Vol. XXX, 1900, pp. 38–43.

in the precipitation of ores. If the contents of half a dozen test tubes filled with solutions chosen at random be dumped together, a precipitate is almost sure to form. And just so sure as underground waters come from this source and that source and mingle in the trunk channels of underground circulation, just so surely are precipitates formed. Fourth, in the formation of an ore deposit the wall rock may contribute a solution which precipitates a metal, or it may contribute a metal which is precipitated by a solution. Consequently an ore deposit may be confined to a particular horizon where there is a certain rock. For instance, lead and zinc are very generally associated with limestone, and the sandstones or other rocks above or below are very likely to be deficient or nearly devoid of these metals. To a less extent other ores show a decided preference for limestone as compared with other rocks. The explanation may be that the limestone itself furnishes the material; and this is believed to be the fact in various cases. The explanation may be that the limestone furnishes a precipitating agent to solutions derived from other rocks. It may be that the limestone because of its ready solubility furnishes large openings in which big deposits may be formed. Finally the explanation may lie in the combination of two or more of these factors. I have no doubt if we consider the whole world each of these factors is important, and that in some cases all of them coöperate. As a result of the combination of the various factors above considered a porous rock or an opening once in a million or ten million times receives enough of the metallic materials in solution so that a fraction of an ounce of gold per ton, or a few ounces of silver per ton, or a few per cent. of copper or some other metal, or a large per cent. of iron, will be precipitated; and we call the material an ore deposit. An ore deposit it is from an economic point of view. From a geological point of view it is usually to a far greater extent quartz and calcite and other gangue minerals.

I wish now to go a little further and consider the fissure on the slope shown in this chart (Fig. 6), both in the past and the

present. At some distant time in the past suppose the surface and level of groundwater, instead of being as shown, were at much higher levels, having since been greatly lowered by the processes of denudation. Where would the upper part of the fissure shown, the water of which is descending, be with reference to the circulation at that time? It would be where the lower part of the fissure now is, would it not? It would be where the waters are ascending, as shown in the lower part of the fissure. Therefore for the part of the fissure where the water is now descending it may be that the first contribution of ore was made by ascending waters, although descending waters are now the only important factor. But as denudation went on the condition would gradually change. The part of the fissure under consideration would pass through a stage in which the waters would mainly come in laterally. As denudation went still farther the waters might all be descending, and in the extension of the fissure below the waters might come in laterally, and still deeper might be ascending. We must now still further amplify our theory, must we not? To explain the entire ore deposit we have to consider all parts of the ore deposit throughout its entire history. At present ore deposition by descension, by lateral secretion, by ascension, is somewhere occurring in the fissure; but not only is this the case, but all have worked in turn in the upper part of the deposit. Therefore this further complicates the theory of ore deposition.

Now I wish to give some facts as to the actual occurrences of ore deposits before I go to the next step in theory. At Butte, Mont., are famous copper deposits. In the copper lodes of this district, in the very upper part of the deposits, above the level of groundwater, there were oxidized ores which carried high values in silver and gold, but very low values in copper. At and a short distance below the level of groundwater there were very high values in copper as sulphides. "There follows below a region of varying height, of valuable rock, which again slowly deteriorates in depth; this deterioration, however, being so retarded finally as to be scarcely

appreciable."[1] This deep ore is mainly copper-bearing pyrites. Douglass tells us that in depth every copper deposit of the entire Appalachian region of the United States shows only cupriferous pyrrhotite. An excellent illustration is Ducktown, Tenn., where at the level of groundwater was a very rich deposit of chalcocite but a few feet thickness which rapidly changed into very low grade cupriferous pyrrhotite.[2] In Australia down to the level of groundwater are high values in native gold; below the level of groundwater are auriferous pyrites bearing relatively small values of the precious metals.[3] Some of the superintendents say where ounces of gold are found above the level of groundwater only pennyweights are found below.[4] In the Sierra Nevada of the United States, according to Lindgren,[5] above the level of groundwater the gold values ran from $80 up to $300 per ton; but below the level of groundwater where there are sulphurets the values average from $20 to $30 per ton. Notwithstanding the fact that occurrences such as those mentioned are typical of the ore deposits of many districts of the world it has been believed by very many practical mining men that ore deposits become richer upon the average with increase of depth; but it must be admitted that the facts do not justify this sanguine expectation. In fact nine mines out of ten, taking the world as a whole, are poorer the second 300 meters than they are the first 300 meters, and are poorer the third 300 meters than they are the second 300 meters. In fact, many

[1] The Ore Deposits of Butte City, by R. C. BROWN: Trans. Am. Inst. Min. Eng., Vol. XXIV, 1895, p. 556.

[2] The Persistence of Lodes in Depth, by W. P. BLAKE: Eng. Min. Jour., Vol. LV, 1893, p. 3.

The Ducktown Ore Deposits and Treatment of the Ducktown Copper Ore, by C. HENRICH: Trans. Am. Inst. Min. Eng., Vol. XXV, 1896, pp. 206–209.

[3] The Alterations of the Western Australian Ore Deposits, by H. C. HOOVER: Trans. Am. Inst. Min. Eng., Vol. XXVIII, 1899, pp. 762–764.

[4] The Genesis of Certain Auriferous Lodes, by J. R. DON: Trans. Am. Inst. Min. Eng., Vol. XXVII, 1898, p. 596.

[5] The Gold-quartz Veins of Nevada City and Grass Valley, California, by WALDEMAR LINDGREN: Seventeenth Ann. Rep. U. S. Geol. Surv., 1895–6, Pt. II, p. 128, 1896.

ore deposits have been exhausted or have become so lean as not to warrant working before the 300 meter level is reached; a large proportion before the 600 meter level is reached; while comparatively few ore deposits have been found to be so rich as to warrant working at depths greater than 1000 meters.

There are however some ore deposits which are not known to decrease in richness with depth so far as yet exploited. There are a considerable number of deposits in which after a first rapid decrease in richness maintain their tenor pretty well to the depth of 300, 500 or even 1000 meters, and some few deposits maintain their richness at even greater depths. But we cannot reasonably hope that a deposit will get richer with depth provided we use a 300-meter unit for measurement. The most sanguine view which is ever justified for any deposit is that, using a 300-meter unit, that the second shall be as good as the first, and the third as good as the second. While the above is true there are very great irregularities in the richness of ore deposits, both favorable and unfavorable, due to multifarious causes, which I cannot possibly discuss tonight, but which I considered somewhat fully in the Institute paper.[1] These irregularities are especially marked in the upper 300 meters of a deposit; so that in many cases if the unit of measurement were 10 meters or 30 meters, or in a few cases 100 meters even, it might be said that deposits are becoming richer with depth; although the reverse also occurs in many cases. The truth is that in the uppermost part of an ore deposit the variations in richness with depth are extreme, and no definite rules can be laid down in reference to them.

Now what is the explanation of these irregularities and of the very general diminution of richness with depth? What is the explanation in some cases of the relatively even values at variable depth? The last question will be first considered.

In those instances in which the tenor is maintained or practically maintained from the surface to a great depth the ore

[1] Some Principles Controlling the Deposition of Ores, by C. R. VAN HISE: Trans. Am. Inst. Min. Eng., Vol. XXX, 1900, pp. 102–112.

is believed to be the result of a single concentration by ascending waters. Such ore deposits may continue without any appreciable diminution in richness to the lowest limits to which man may expect to penetrate the earth; but these are exceptional cases. Even ore deposits which are the result of a single concentration by ascending water may diminish in richness at considerable depth. It has been seen that in the fissure at the bottom of the valley on this chart (Fig. 6) that the water ascends to the surface. It is evident that the upper part of the fissure receives the greatest supply of water, and this water to a large extent does not penetrate any great depth; while the lower part of the fissure receives less water, but this water penetrates to a considerable depth. It may happen that the water relatively near the surface traverses the rocks containing the main supply of metals and therefore brings the chief contributions of valuable material, or such waters may carry the precipitating agent. In such instances the ore deposits produced by ascending water alone, would diminish in richness with depth; but such decrease would not be likely to be very rapid. Upon the other hand, if the above conditions be reversed, a deposit may increase in richness for a considerable depth; but as a matter of fact this appears to be a very infrequent case.

As illustrations of the ore deposits of the class produced by ascending waters alone are the copper deposits of Lake Superior. These deposits, while very bunchy and extremely irregular in the distribution of copper, are wonderfully persistent in depth. The copper of the ore was deposited in the metallic form. As compared with sulphides, this material is not readily oxidized. In this district the rocks above the level of groundwater are not appreciably weathered. Doubtless there was a belt of weathered material before the glacial epochs, but if so, it has been swept away by ice erosion; and since the glacial period sufficient time has not elapsed to weather appreciably the rocks which now lie within the theoretical belt of weathering. If there once were in this district an upper belt of weathering in which there were deposits of exceptional richness, this

material has been removed. However, in this district, a first concentration by ascending waters was adequate, but it is not often that a first concentration produces deposits of such richness as those adjacent to Calumet and Houghton on Keweenaw Point; and, indeed, this is exceptional even in the Keewenawan of the Lake Superior region; for while concentrations of copper have occurred at many points in the rocks of this period, as yet at no other locality have those concentrations been found to be so abundant and rich as to warrant exploitation on a large scale.

I now turn to the question as to the cause of frequent diminution of richness of ore deposits with depth. Many or most of such ore deposits are believed to be the products of two concentrations, the first by ascending, the second by descending waters. In this connection it is necessary to call attention to the fact that a large proportion of the ore deposits which are being exploited are below some part of a slope. It may be said that the reason for this is that the low grounds are more difficult to explore and work; but giving due allowance for this, it still seems to me that the majority, perhaps the great majority, of very rich deposits are below slopes and crests, and not below the valleys. I believe the richer deposits are below the slopes, because at these places a second concentration is possible and probable.

Returning now to this chart (Fig. 6) we shall direct our attention to the fissure on the slope. This fissure once extended up through the overlying rocks which have been removed by denudation. What has become of the ore in the part of the fissure which has been worn away? If, for instance, it carried 5 per cent. of copper, what has become of it? A part of it would have been scattered far and wide through erosive action; but a part of it would have been taken into solution and redeposited in the same vein deeper down. In the belt of weathering oxidized salts, such as sulphates, would form; the descending waters would carry these products downward; and it is my belief that they would react upon the solid, lean sulphides below with the result of precipitating the metals from the descending solutions.

Now this has been held to be a mere unverified assumption by some geologists, but it seems to me that they have not fully considered the certain effects of the chemical laws concerned. We know if in a laboratory a solution of copper sulphate or other copper salt be placed in contact with iron sulphide, that copper will be thrown down as copper sulphide. If the copper solution be placed in contact with a lean copper-iron sulphide, a sulphide richer in copper will be produced. And if these reactions occur in the chemical laboratory, will they not as certainly occur in the laboratory of nature, although perhaps more slowly?

At this point it is to be recalled that in many copper deposits above the level of groundwater oxides and carbonates occur, while below the level of groundwater are sulphides. Moreover, at high levels these sulphides are rich in copper, and they usually become poorer in copper sulphide and richer in iron sulphide at the lower levels. You will remember at Butte, Mont., at and for a distance below the level of the groundwater, are rich copper sulphurets which grade at depth into leaner copper sulphides containing correspondingly large amounts of iron sulphide. You will remember the same is true for the entire Appalachian region. You will remember that frequently above the level of groundwater gold lodes are exceedingly rich. What is the explanation of these and similar facts? What is the explanation of the exceptional or even extraordinary richness of the deposits at and near the level of groundwater, and of the low grade of cupriferous pyrites deep below the level of groundwater. In my opinion the only plausible explanation is that the rich parts of the deposits have received two concentrations, the first by ascending waters and the second by descending waters. The metals of the rich portions of the deposits were largely contributed by the parts of the deposit above, or once above, the rich parts. In some cases portions of the depleted veins remain, as at Butte; but frequently the depleted parts of the veins have been removed by erosion. The remote source of the material was, therefore, the metals deposited by the first concentration.

But let us follow the matter still farther. In the majority of cases, as denudation continued, the parts of the ore deposits produced by the second concentration rise into the belt of weathering. They may there be partly or wholly transformed into rich oxidized products, or they may be depleted to extend the rich deposits below. In the concentration by descending waters the chief chemical reactions are believed to be between the oxides or salts of copper and the sulphide of iron. The precipitation of copper sulphide resulting may occur in various ways.

The reaction may produce chalcopyrite, as shown by the following equations:

$CuSO_4 + 2FeS = CuFeS_2 + FeSO_4$, or

$CuSO_4 + 2FeS_2 + O_4 = CuFeS_2 + FeSO_4 + 2SO_2$.

The reactions may produce bornite, as shown by the following equations:

$Cu_2SO_4 + CuSO_4 + 3FeS = Cu_3FeS_3 + 2FeSO_4$, or

$Cu_2SO_4 + CuSO_4 + 3FeS_2 + 6O = Cu_3FeS_3 + 2FeSO_4 + 3SO_2$.

Or the reactions may directly produce chalcocite, as shown by the following equations:

$Cu_2SO_4 + FeS = Cu_2S + FeSO_4$, or

$Cu_2SO_4 + FeS_2 + O_2 = Cu_2S + FeSO_4 + SO_2$.

If the reactions are between a copper salt and sulphide bearing copper various reactions throwing down the copper may also occur. The reactions may be upon chalcopyrite producing bornite, as shown by the following equation:

$2CuFeS_2 + CuSO_4 + O_2 = Cu_3FeS_3 + FeSO_4 + SO_2$.

It may be the reaction of copper sulphate upon chalcopyrite or bornite producing chalcocite, as shown by the following:

$CuFeS_2 + CuSO_4 + O_2 = Cu_2S + FeSO_4 + SO_2$, or

$Cu_3FeS_3 + CuSO_4 + O_2 = 2Cu_2S + FeSO_4 + SO_2$.

It may be by the reaction of copper oxide or copper sulphate upon covellite producing chalcocite, as shown by the following equations:

$6CuS + 2Cu_2O = 5Cu_2S + SO_2$, and

$6CuS + 2Cu_2SO_4 + 3H_2O = 5Cu_2S + 2H_2SO_4 + H_2SO_3$.

Parallel sets of reactions could be, and indeed are written in my full paper upon the subject of ore deposits, which explain the formation of the rich sulphides of lead, zinc, and silver through the reactions of the oxidized products of these metals upon sulphide of iron, producing rich sulphides of lead, zinc, and silver. However time does not suffice to present these this evening. The particular reaction in an individual case will depend upon the relative solubilities of the various compounds present, upon the law of mass action, upon the pressure and temperature, and upon various other factors.

Now I do not assert of the equations which have been written for copper and the other metals that the reactions represented occur exactly as written, but I do assert that reactions of the general character represented occur by which the oxidized products of the metals in solution are thrown down by the lean sulphurets, producing rich sulphurets. I have no doubt that many other reactions besides those written take place. It is exceedingly difficult to ascertain the particular reactions which occur at a given time and place; but I think it is perfectly clear that reactions occur of the type of those written. I cannot attempt to give you all the evidence on the point, but to me the case is demonstrative. If this be correct we now have an explanation of the fact that a great many ore deposits are rich at high levels and become poorer with depth. These ore deposits have undergone two concentrations, a first concentration deposited by ascending waters and a second concentration deposited by descending waters. The supplies for the first concentration were obtained from the widely dispersed and small amounts of material disseminated through the rocks. The supplies for the second concentration were derived from an earlier concentration.

In the foregoing statements the second concentration of metals by solution, downward transportation, and precipitation by reactions upon the sulphides of an earlier concentration has been emphasized. However, it is not supposed that this is the only process which may result in enrichment of the upper parts of ore-deposits by descending waters. The enrichment of this

belt may be partly caused (1) by reactions between the downward moving waters carrying metallic compounds and the rocks with which they come in contact, and (2) by reactions due to the meeting and mingling of the waters from above and the waters from below.

(1) The metallic compounds dissolved in the upper part of the veins, carried by descending waters, may be precipitated by material contained in the rocks below. This material may be organic matter, ferrous substances, etc. So far as precipitating materials are reducing agents, they are likely to change the sulphates to sulphides, and precipitate the metals in that form. While sulphides may thus be precipitated either above or below the level of groundwater, they are more likely to be thrown down below the level of groundwater. Other compounds than reducing agents or sulphides may precipitate the downward moving salts in other forms than sulphides.

(2) In a trunk-channel, where waters ascending from below meet waters descending from above, there will probably be a considerable belt in which the circulation is slow and irregular, the main current now moving slowly upward and now moving slowly downward, and at all times being disturbed by conventional movements. Doubtless this belt of slow general movement and conventional circulation would reach a lower level at times and places of abundant rainfall than at other times and places, for under such circumstances the descending currents would be strong. The ascending currents, being controlled by the meteoric waters falling over wider areas, and subject to longer journeys than the descending currents, would not so quickly feel the effect of abundant rainfall. Later, the ascending currents might feel the effect of the abundant rainfall and carry the belt of upward movement to a higher level than normal. However, where the circulation is a very deep one, little variations in ascending currents result from irregularities of rainfall.

In the belt of meeting ascending and descending waters (see Fig. 6) conventional mixing of the solutions due to difference in temperature would be an important phenomenon. The waters

from above are cool and dense, while those from below are warm and less dense. In the neutral zone of circulation the waters from above would thus tend to sink downward, while waters from below would tend to rise, and thus the waters would be mingled. Still further, even if the water were supposed to be stagnant at the neutral belt, it is probable that by diffusion the materials contributed by the descending waters would be mingled with the materials contributed by the ascending waters.

Ascending and descending solutions are sure to have widely different compositions, and precipitation of metalliferous ores is a certain result. As a specific case in which precipitation is likely to occur, we may recall that waters ascending from below contain practically no free oxygen and are often somewhat alkaline, while waters descending from above are usually rich in oxygen and frequently contain acids, as at Sulphur Bank, described by Le Conte.[1] The mingling of such waters as these is almost sure to result in precipitation of some kind. Le Conte further suggests[2] by the mingling of the waters from below with those from above that the temperature of the ascending column will be rapidly lessened, and this also may result in precipitation, but the dilution would work in the reverse direction.

The metals precipitated by the mingling of the waters may be contributed by the descending waters, by the ascending waters, or partly by each. In so far as more than an average amount of metallic material is precipitated from the ascending waters, this would result in the relatively greater richness of the upper part of veins independently of the material carried down from above.

In all the cases considered the precipitation and enrichment of the upper parts of deposits follow from the reactions of downward moving waters. Their effect may be to precipitate the metals of the ascending water to some extent and thus assist in the first concentration. But the results of these processes

[1] On the Genesis of Metalliferous Veins, by JOSEPH LE CONTE: Am. Jour. Sci., 3d ser., Vol XXVI, 1883, p. 9.

[2] LE CONTE, op. cit., p. 12.

cannot be discriminated from the concentration resulting from an actual downward transportation of the material of an earlier concentration. In concluding this part of the subject, *It is held that the downward transportation of metals already in lodes is the most important of the causes explaining the character of the upper portions of ore deposits; and that their peculiar characters are certainly due to the effect of descending waters.*

The concentrations by ascending and descending waters have been considered as if they were mainly successive. In some instances this may be the case; but it is much more probable that ascending and descending waters are ordinarily at work upon the same fissure at the same time, and that their products are, to a certain extent, simultaneously deposited. For instance, under the conditions represented by this chart (Fig. 6) a first concentration by ascending waters is taking place in the lower part of the fissure, and a reconcentration by descending waters is taking place in the upper part of the fissure. Between the two there is a belt in which both ascending and descending waters are at work. The rich upper part of an ore deposit which is worked in an individual case may now be in the place where ascending waters alone were first acting, where later, as a consequence of denudation, both ascending and descending waters were at work, and still later, where descending waters alone are at work. The more accurate statement concerning ore deposits produced by ascending and descending waters, is, therefore, that ascending waters are likely to be the potent factor in an early stage of the process, that both may work together at an intermediate stage, and that descending waters are likely to be the potent factor in the closing stage of the process.

Also, for the sake of simplicity in the consideration of the concentrations I have disregarded the lateral elements of the moving water. In many cases superimposed upon the vertical movements in the fissures or other openings are lateral movements, as a result of which the deposits instead of being in vertical positions are inclined, often much inclined, and indeed may be horizontal or even locally descending. Moreover the

horizontal extents of the deposits may be much greater than the vertical extents. Reduced to a simple and broad statement, *The first concentration of many ore deposits is the work of a relatively deep water circulation, while the reconcentration is the result of reactions upon an earlier concentration through the agency of a relatively shallow water circulation. Commonly the deep water circulation is lacking in free oxygen and contains reducing agents, and the shallow water contains free oxygen. The deep water is therefore a reducing, and the shallow water an oxidizing agent.*

In addition to the general factors already considered there are many special factors which have a most important, indeed, very often a controlling influence in the production of ore-chutes and in the localization of ore in certain areas and districts. Some of these factors are the complexity of openings, the presence of impervious strata at various depths, the presence of pitching folds, the character of the topography. I see however that my time is nearly gone, and I shall not take up their discussion this evening, but must refer those especially interested in this phase of the subject to my full paper already repeatedly mentioned.[1] I must however note that impervious strata are frequently of controlling importance in the underground circulation. Often deep and shallow water circulations are separated by such strata. Often also as the result of the removal of impervious strata by denudation, the previous deep circulation ceases and the action of the shallow circulation is inaugurated.

At this point it may be well to briefly recall the most fundamental features of the water circulation which produces the ore deposits. First comes the downward-moving, lateral-moving waters of meteoric origin which take into solution metalliferous material. These waters at depth are converged into trunk channels, and there, while ascending, the first concentration of ore deposits may result. After this first concentration many of the ore deposits which are worked by man have undergone a later concentration not less important than the earlier, as a result of

[1] Some Principles Controlling the Deposition of Ores, by C. R. VAN HISE : Trans. Am. Inst. Min. Eng., Vol. XXX, 1900, pp. 112–146.

shallow descending or lateral-moving waters. In other cases a concentration by descending, lateral-moving waters alone is sufficient to explain some ore deposits. It thus appears more clearly than heretofore that an adequate view of ore deposits must not be a descending-water theory, a lateral-secreting water theory, or an ascending-water theory alone. While an individual ore deposit may be produced by one of these processes, *For many ore deposits a satisfactory theory must be a descending, lateral-secreting, ascending, descending, lateral-secreting theory.*

But there is no question in my mind that this theory is still insufficient to fully explain many of the ore deposits. No knowledge is ever complete. We move step by step, carrying a theory nearer and nearer completion. If, however, a theory be based on good work, it usually will not prove to be false; it will be found to be incomplete. Sandberger was not wrong when he said lateral secretion explained many things in reference to ore deposits. He was wrong only when he excluded other factors. He became unscientific when he carried his theory further than his observations justified. While the theory here proposed is believed to make an important advance, it will sooner or later be found to be incomplete. I trust it will not be found to be false. But the most that I can hope for it is that it is approximately correct as far as it goes.

It is believed that the principles which have been presented lead to a new and natural classification of the ore deposits produced by underground water. As already noted, ore deposits may be divided into three groups: (1) ores of igneous origin, (2) ores which are the direct result of the processes of sedimentation, and (3) ores which are deposited by underground water.

Since the ores produced by igneous agencies and those produced by processes of sedimentation have not been considered in this paper, a subdivision of these groups will not be attempted.

Ores resulting from the work of groundwater, group (3) above, may be divided into three main classes:

(*a*) Ores which at the point of precipitation are deposited by ascending waters alone. These ores are usually metallic or

some form of sulphuret; but they may be tellurides, silicates, or carbonates.

(*b*) Ores which at the place of precipitation are deposited by descending waters alone. These ores are ordinarily oxides, carbonates, chlorides, etc., but silicates and metals are exceptionally included.

(*c*) Ores which receive a first concentration by ascending waters and a reconcentration by descending waters. The concentration by ascending waters may wholly precede the concentration by descending waters, but often the two processes are at least partly contemporaneous. The materials of class (*c*) comprise oxides, carbonates, chlorides, and rarely metals and silicates above the level of groundwater, and rich and poor sulphurets, tellurides, metallic ores, etc., below the level of groundwater. At or near the level of groundwater, these two kinds of products are more or less intermingled, and there is frequently a transition belt of considerable breadth.

How extensive are the deposits of class (*a*) I shall not attempt to state. Indeed, I have not such familiarity with ore deposits as to entitle me to an opinion upon this point. However a considerable number of important ore deposits belong to this class. This class is illustrated by the Lake Superior copper deposits.

The ore deposits of class (*b*) are important. Of the various ores here belonging probably the iron ores are of the most consequence. A conspicuous example of deposits of this kind are the iron ores of the Lake Superior region.

It is believed that the ore deposits of class (*c*) are by far the most numerous. I suspect that a close study of ore deposits in reference to their origin will result in the conclusion that the great majority of ores formed by underground water are not the deposits of ascending waters alone, but have by this process undergone an early concentration, and that descending waters have produced a later concentration, as a result of which there is placed in the upper 50 to 500 or possibly even 1000 meters of an ore deposit a large portion of the metalliferous material

which originally had, as result of the early concentration, a much wider vertical distribution.

To the foregoing classification objections will at once be made: It will be said that there are no sharp dividing lines between the groups and classes. To this objection there is instant agreement. Transitions are everywhere the law of nature. It is well known that there are gradations between different classes of rocks,[1] and this statement applies equally well to ore deposits. I even hold that there is gradation between ore deposits which may be explained wholly by igneous agencies and those which may be explained wholly by the work of underground water or by processes of sedimentation.

I have elsewhere held that there is complete gradation between waters containing rock in solution and rock containing water in solution.[2] If there be no sharp separation between water solutions and magma it is probable that this is also true in reference to ore deposits of direct igneous origin and those produced by underground water. There may be ore deposits in which water action and magmatic differentiation have been so closely associated that one cannot say whether the resultant ore deposit is mainly a water deposit or mainly a magmatic deposit. But for the vast majority of ore deposits, if I properly apprehend the relations, the broad general statements which I have made apply. Ordinarily there is little difficulty in discriminating between veins and dikes, the first representing crystallizations from water solutions, the second crystallizations from magma. There are few cases where the discrimination in reference to ore deposits is not easy. While gradations between water deposited ores and igneous ores are uncommon, gradations between the different classes of ore deposits formed by underground water are common.

Ores which have received a first concentration by igneous agencies or by processes of sedimation are sure to be reacted upon by the circulating underground waters, and thus a second

[1] The Naming of Rocks, by C. R. VAN HISE: Journ. of Geol., Vol. VII, 1899, pp. 687, 688.

[2] Principles of North American pre-Cambrian Geology, by C. R. VAN HISE: Sixteenth Ann. Rept. U. S. Geol. Surv., 1894–5, Pt. I, p. 687.

or even a third concentration may take place. The first concentration by igneous or sedimentary processes may be the more important or dominant process, or the additional concentration or concentrations by underground waters may be the more important or dominant process. In some cases therefore the ores may be referred to as produced by igneous agencies, in others as produced by processes of sedimentation, in others as produced by these in conjunction with underground waters, and in still others as produced mainly by underground waters.

Ore deposits which are precipitated almost solely by ascending waters will grade into those in which descending waters have produced an important effect, and thus there will be transition between classes (*a*) and (*c*). Similarly there will be every gradation between classes (*a*) and (*b*) and between classes (*b*) and (*c*). If this be so it will not infrequently happen that a single fissure may fall partly in one class and partly in another. Thus a single ore deposit may belong partly in class (*a*) and partly in class (*c*). However, in most cases the workable part of a deposit will largely belong to one of the three classes.

Not only are there gradations between different varieties of the ore deposits, but there are gradations between the ore deposits and the rocks; for the ore deposits in many cases are not sharply separated from the country rocks, but grade into them in various ways.

In answer to the above objection concerning gradations, it may be said that I know of no classification of ore deposits which has yet been proposed to which the same objection may not be urged with equal or greater force.

However this retort does not give any criterion by which the usefulness of the above classification may be tested. The test is, does this classification give a more satisfactory method of studying ore deposits than has heretofore been possible? Will an attempt to apply this classification assist mining engineers and geologists in accurately describing ore deposits? Will the classification to a greater extent than any previous one give engineers rules to guide them in their expenditure in exploration

and exploitation? By these criteria I am willing that the classification shall be tested.

As an illustration of the practical usefulness of the classification is the connection between genesis and depth. The character of a deposit in most cases will determine to which class it belongs. Where the ores are deposited by ascending waters alone it has been pointed out that this is favorable to their continuity to great depth. Therefore, where a given ore deposit has been shown to belong to this class, the expenditure of money for deep exploration may be warranted, although, as already pointed out, p. 757, such deposits may decrease in richness with depth. Where a deposit is produced by descending waters alone, the probable extent in depth is much more limited. In such cases, when the bottom of the rich product is reached, it would be the height of folly to expend money in deep exploration. Where the ore deposit belongs to the third class, that produced by ascending and descending waters combined, there will, again, be a richer upper belt composed of rich oxidized and sulphureted deposits which we cannot hope will be duplicated at depth. To illustrate: it would be very foolish, at Ducktown, Tenn., to sink a drill hole or shaft into the lean cupriferous pyrrhotite with the hope of finding rich sulphurets such as those which were mined near the level of groundwater. Those who have spent money in deep prospecting of the lean pyrrhotite in the Appalachian range will doubtless agree to this statement. Deposits produced by two concentrations may grade into the class produced by ascending water alone, and after the transition the deposit may be rich enough to warrant exploitation at depth; but if such work be undertaken it must be done with the understanding that the rich upper products will not be reduplicated at depth. It therefore appears to me that the determination to which of the classes of ore deposits produced by underground waters a given ore deposit belongs has a direct and very important practical bearing upon its exploration and exploitation.

C. R. Van Hise.

Reviews

Secondary Enrichment of Ore Deposits. By S. F. Emmons. Trans. American Inst. Min. Eng., Vol. XXX, 40 pp., 1900.

Enrichment of Gold and Silver Veins. By Walter Harvey Weed. Trans. Amer. Inst. Min. Eng., Vol. XXX, 25 pp., 1900.

In the exploitation of ore bodies it has been found that many deposits decrease in richness as depth increases. The explanations have been various. That the phenomenon is a far more general one than was once supposed, has only recently been recognized in its full significance. It may be expected to be very frequently met with, now that its real character has been found out, by all students of ore deposition.

It is now a well-known fact that as geological formations, ore-bodies as a rule are to be regarded as deposits originating very near the surface of the earth's crust; or, to be more precise, in the thin outer belt of the zone of fracture of the lithosphere. The unusual richness of many ore deposits at very shallow depths has come to be considered as due to local enrichment, often long after the first concentration has taken place.

From the viewpoint of origin, diminution of richness with depth is not, then, to be ascribed to actual depreciation in the original grade of the ore. The real status of the case is that the deposition of ore has, in the upper belt, undergone a greater or less augmentation in metallic content since the body was first formed.

Among those who have given the subject of ore genesis most attention, and especially among those who have approached the subject from the geological side, the rival theories of ascending solutions, descending solutions, and laterally moving solutions, no longer find countenance as distinct processes. Ore deposition may take place through all three means, which may have equal importance. After an ore deposit has once formed under special geological conditions, the secondary enrichment which it may undergo is believed to take place largely under the influence of the descending solutions.

In the exploitation of the ore-bodies, it all goes to show how vitally important is a full consideration of the geological structures presented at the time of the first concentration, and as subsequently assumed.

The keynote of Mr. Emmons' paper is given in one of the opening paragraphs, when he says that "admitting fully the general truth of the statement that the descending surface waters exert an oxidizing action, and hence that oxidation products within the reach of surface waters are the result of the alteration by the latter, I have been led to believe, by observations now extending over a considerable number of years, that under favorable conditions the oxidation products may be changed back again into sulphides and redeposited as such, thus producing what may be called a sulphide enrichment of the original deposits. . . . . Being rather a searcher after facts than a theorist, I am not deterred from accepting what may appear to me the correct reading of observed facts, because it seems to contradict generally accepted theories."

After briefly discussing the circulating waters of surface origin, the groundwater level, the deposition of oxides below water-level, and the deposition of sulphides, the author goes on to give an account of many cases of secondary enrichment which his wide experience has brought to notice. This account occupies the greater part of the paper. The three propositions following are believed to be substantiated by the geological evidence adduced:

1. That descending waters not only cause migrations, or transference and reconcentration, of the alteration products of the original vein-materials in oxidized form, producing in one place an enrichment, and in another possibly an impoverishment of the original deposit, but that in their further downward course the oxidized forms are frequently reduced and redeposited as sulphides, thereby producing a sulphide enrichment of the original vein-materials.

2. That this secondary enrichment of sulphides is not necessarily a reduction in the presence of organic matter, but is frequent where no organic matter can be supposed to be present. It occurs mainly in contact with the original sulphides of the deposits, and is, presumably, a result of chemical reaction between these sulphides and the materials brought down in solution by the descending waters.

3. That while this redisposition of sulphides in many cases appears to commence at or near the groundwater-level, it does not appear to

have a necessary connection with that level, and may under favorable conditions extend below that level for a distance as yet undetermined, the most important favoring conditions appearing to be recent or post-mineral fractures, which have admitted a relatively free and uninterrupted descent of these waters.

In conclusion, students are cautioned against making the inference too sweeping. "Until a much larger number of ore deposits have been studied with a definite purpose of determining how far they have been subjected to secondary enrichment, it does not seem safe to draw any far-reaching conclusions from the observations and suggestions noted above. It has long been recognized that the superficial alteration of ore deposits has often produced a very considerable modification of the original constitution of the deposit, and its alteration has so frequently been in the nature of an enrichment in the more valuable metals relatively to the original tenor of the ores, that it has given rise to the very hasty decision that all ore-deposits necessarily become poorer in depth, which is almost as unjustifiable as the old assumption by the miner, that the nearer he got to the source of his ore in the unknown deposits, the richer it would become.

"The fact that ores under some conditions may be removed and redeposited as sulphides, even below groundwater-level, opens a wide field of possibility in accounting for the unusually rich bodies of ore that are in some mines found in the middle levels, and have been fruitlessly sought for at greater depth. In many cases these have undoubtedly resulted from a concentration of material leached down from the upper portions of the deposit as they have been worn down and carried away by denudation. Especially in the case of large bodies of pyritous ore carrying small proportions of more valuable metals, is a concentration of those metals by downward percolating solution to be looked for. It is, however, not yet safe to say that all rich bonanzas in vein deposits have necessarily been formed in this way."

The paper by Mr. Weed gives a brief statement of the theory enunciated in a former contribution. The principles are applied more particularly to the deposits of the precious metals, with special emphasis laid upon the dependence of such enrichments upon the presence of iron sulphide in the primary ore, and upon the structural features which control the circulation of the enriching solutions below groundwater-level. The discussion is largely of Montana deposits, which the author has been engaged in studying for several years past. Regarding

the theoretical chemical changes, those taking place in each of the several zones are considered in detail.

Leaching out of the metals from the portion of the vein lying above groundwater-level is considered as the main source of the enriching materials. The alteration at the surface leaves the iron as a gossan, while the waters carrying the gold, silver, copper, and other metals in solution trickle downward through the partially altered ores into cracks and water-courses which penetrate the ore-body below the water-level. The first of the process is, therefore, the leaching of the lean ores which occurs in the superficial alteration of the vein. In weathering, the sulphides oxidize according to their relative affinity for oxygen and inversely as their affinity for sulphur. It is concluded from the evidence that ore-bodies lacking in iron pyrite will not show enrichment, thus explaining the absence of any such phenomena in the pure silver-lead bodies of the Coeur d'Alene district and elsewhere.

The observations of the author on the effects of physiographic and climatic changes, and on the changes of water-level, are of exceptional significance: "Active degradation favors the accumulation of enrichment, while prolonged degradation of a region, resulting from physiographic revolutions, may result in successive migrations of material and the accumulation in a relatively shallow zone of the metals derived from many hundreds, and possibly thousands, of feet of the vein worn away in the degradation of the land. Climatic conditions, rainfall or aridity, warmth and rapid alteration of vein fractures, are agents affecting surface weathering, and hence, also, enrichment.

"Active degradation of a region, that is, rapid weathering, favors enrichment by the quickness with which it removes the upper already leached part of the vein, so that a larger amount of the vein-matter is lixiviated in a given time than would result from the slower wasting of the land. Such enrichments are favored by high latitudes. Moreover, the mountainous regions are those in which secondary fractures are most apt to be found.

"Prolonged degradation is favorable for a similar reason, since time is a factor in enrichment and changes in elevation, etc., affect the rate and the progress of decay of the vein; while the crustal movements accompanying the physiographic changes favor fracturing of the earlier deposit, increasing facility of leaching and place for deposition. If a region passes through several cycles of erosion and elevation, it is evident that their result is likely to be a succession of enrichments in

which not only the original ore is leached, but the earlier enrichment deposits migrate downward. At Butte, Mont., the region has passed through several very pronounced changes in elevation since the formation of veins in Tertiary time. In early Tertiary time the present topography of the region was blocked out, and mountain ranges and deep valleys carved. This was succeeded by earth movements by which the streams became clogged or the valleys dammed, forming lakes; while volcanoes broke out at numerous places and showered ashes and scoria over the region. The valleys were silted up or in part filled with volcanic débris before crustal movements drained the valleys and altered the divides. More recent movement, possibly still continuing, is marked by faults and a reversing of the stream courses. The old valley at Butte is filled by hundreds of feet of débris, and a mountain wall 2500 feet high marks a north and south fault-line. These changes all caused a migration of water-level facilitating the processes of weathering and enrichment, and the great bodies of rich copper ores of the region are believed to be in part due to this cause."

CHARLES R. KEYES.

Enrichment of Mineral Veins by Later Metallic Sulphides. By WALTER HARVEY WEED. Bull. Geol. Soc. Am. Vol. XI, pp. 179–206, 1900.

The author calls attention to the occurrence of localized masses of exceptionally rich ore in mines of copper, silver and zinc, which he undertakes to explain as the result of enrichment by processes subsequent to the deposition of the lower grade ore. The paper attempts to show that these richer bodies of sulphide ore are formed by the redeposition of material leached from the vein, generally by superficial waters, and to show the chemical and mineralogical changes involved, as well as the physical conditions under which redeposition took place. The ores in question are chiefly the high grade sulphides.

He describes three zones; that of oxidation, that of sulphide enrichment, and that of primary sulphides, and refers to the writings of DeLaunay, Prosepny, Penrose, Emmons and Kemp in this connection. In discussing the chemical and mineralogical changes supposed to take place, he compares unaltered and altered ore and drainage waters observed by himself and cites freely from the literature of the subject, concluding that together they show that the original ore is

leached by surface waters, which take into solution various metals and passing downward meet with and are decomposed by the sulphides of iron present in the unaltered ore, resulting in the redeposition of new sulphides of the metals.

This is followed by a description of the mode of occurrence of secondary sulphide ores of copper, silver, and zinc, as studied by the author and others. The enrichment in many cases proceeds along barren fractures producing bonanzas. In others it forms films, pay-streaks, or ore shoots in the body of leaner original ore. In still other cases the alterations are produced by deep-seated uprising waters acting upon the vein. As a consequence of these processes veins do not increase in richness in depths below the zone of enrichment.

J. P. I.

Origin and Classification of Ore Deposits. By CHARLES R. KEYES. Trans. American Inst. Mining Eng., Vol. XXX; 34 pp., 1900.

The various attempts that have been made in the past to formulate a rational and at the same time a useful classification of ore deposits have met with only indifferent success. The fundamental factor in the proposed scheme by Dr. Keyes is geological in nature. It is based upon the principle that local deposition and specific form of the ore body is dependent upon geological structures, and these largely govern also the exploitation of the ores. This is believed to be as nearly as it is possible to approach a purely genetic arrangement. The great geological processes are made the governing principles.

Although the present memoir discusses only the classificatory aspects of the ore deposits, it is an application of the modern principles of petrology, and especially those dealing with the processes involved in general rock metamorphism, and it opens the field for fuller explanations and applications of these principles.

Three propositions are emphasized: First, ore bodies with few exceptions are regarded as essentially surface deposits—that is, they are considered as confined to a very thin zone near the earth's surface, or more precisely in the outer belt of the zone of fracture of the lithosphere; second, most of the worked deposits of the globe are thought to be of very late geological formation, probably few dating back before the Tertiary; third, ore bodies are believed to be concentrated chiefly

by circulating waters that have come up from below, down from above, or in from the sides, it being immaterial from which direction.

Of recent years there has been a growing tendency for the large mining companies to pay more attention to the geological features of their properties, and in many cases a regularly trained geologist has been employed. Dr. Keyes emphasizes this fact when he says that "When a specially trained geologist undertakes to make an investigation of a mining property, he first gets his bearings, as it were, with regard to the geological structure of the region and the distribution of the rock formations. At once he eliminates nine tenths of the chances of failure in arriving at the best plan for practical operation. Instead of a great game of chance, the development becomes a strictly business proposition."

After briefly discussing the nature of ore deposits, the general methods of ore formation, and the character of the literature, the criteria for ore classification are formulated. The following table sums up the proposed scheme:

CLASSIFICATION OF ORE DEPOSITS.

Groups.	Categories.	Miners' Forms.
I. HYPOTAXIC. Mainly surface deposits.	Aqueous transportation.	Placers.
	Residual cumulation.	Pockets (in part).
	Precipitative action.	Bog-bodies, some beds, layers.
II. EUTAXIC. Chiefly stratified formations.	Original sedimentation.	Beds, strata, layers.
	Selective dissemination.	Impregnations (in part).
	Emponded amassment.	Masses (in part), some segregations.
	Fold-filling.	Saddle-reefs.
	Crevice accretion.	Gash-veins, stock-works (in part).
	Concretionary accumulation.	Nodules.
	Metamorphic replacement.	Fahlbands (in part), beds.
III. ATAXIC. Predominantly unstratified and irregular bodies.	Magmatic secretion.	Masses (in part), some lenses.
	Metamorphic segregation.	Stocks, lenses.
	Fumerole impregnation.	Contact-veins, some impregnations.
	Preferential collection.	Chambers (in part), some pockets, linked-veins.
	Fissure occupation.	Attrition-veins (in part), some linked-veins, true veins.

The principal points which the memoir dwells upon are:

1. The main feature wherein the scheme of classification offered differs from others is in the prominence given to geological occurrence and the direct operation of the geological processes as essential factors in the genesis of ore bodies.

2. The nearest approach to a purely genetic classification of ore deposits is believed to be found in their geological relationships, as determined by the great groups of geological processes, and not in their direct chemical formation or physical shapes.

3. The chemical reactions so widely used as criteria of ore classification are to be regarded as general agencies, and therefore they are not available in the specific determinations of the various classes of ore bodies.

4. In the discovery and exploitation of ores, structure is of first importance, that is, the structure of the inclosing country rocks.

5. The primary groupings of ore bodies appear to be best indicated when based upon their geological occurrence, as governed by the nature of geological processes operating.

6. The secondary groupings appear to be best based upon the general form of the ore bodies as geological formations produced by the grander geological agencies.

7. The ternary groupings are best based upon the specific phases of the geological processes involved in the formation of ores as ore bodies.

8. The source of the ore materials is an unessential factor in their classification, the great practical question being, how are ores best exploited? In this connection it matters little what was the original condition of the ores. Nor have we to do very much with the detailed, complex, and usually fanciful chemical reactions that are supposed to take place before the final stage of the ore, as we find it, is reached.

9. Ore bodies of very similar appearance may be formed by very different methods—a fact which, while apparent in all classifications, does not necessarily vitiate any.

10. Finally, the proposed scheme is merely suggestive. It is the barest outline of what is believed to be capable of much farther expansion and development into a comprehensive, rational, and practical general plan.

C. F. M.

Éléments de Paléobotanique. By R. ZEILLER. 8vo, pp. 421, with 210 illustrations. Paris: Georges Carré et C. Naud, 1900.

The great needs of recent years in Paleobotany have been a summary of the scattered materials and the delimitation of well-founded data from data that are more or less uncertain. A great stride forward has been taken along these lines and as a result we are in a position to speak more categorically as to plant fossils. The first part of Professor Seward's work appeared sometime ago and has been reviewed in these pages[1]. Almost simultaneously three valuable works have recently appeared, one in English by Professor Scott, one in German by Potonié, and the one which is the subject of this review. The standpoint of the three works is somewhat different, Scott taking the standpoint more of the morphologist, Potonié of the stratigrapher, while Zeiller combines the botanical and geological standpoints, though giving more emphasis to the botanical side. More than any book that has yet appeared, this is a book to be used with impunity by general readers and elementary students. The first chapter treats of the various methods by which plant fossils have been preserved, then follows a chapter on classification and nomenclature. The body of the book, of course, is made up of descriptions of the various fossil forms treated in order. The cuts are simple but clear and good, and the descriptions are doubtless the shortest and clearest that are found anywhere.

The conservatism of the author is shown at many points, and the difference between established and hypothetical data is clearly brought out. As an illustration of this, Zeiller constantly distinguishes between forms based on leaves and forms based on reproductive organs, as in the ferns. There are interesting discussions of the Sphenophylleæ and the Cycadofilices, though the author does not go so far as some in putting these forms in great groups by themselves.

At the close of the book are two chapters of extreme interest. The chapter on the succession of floras and climates is wonderfully meaty, and it is doubtful if a better summary of the known facts was ever written, certainly not in a shorter compass. The author theorizes but little from the facts presented, and such deductions as he makes in regard to climate are extremely conservative. The last chapter must be somewhat startling to many readers, as Zeiller thinks there is very little evidence from fossil plants in favor of gradual evolution. He states that in almost every case, species, genera, families, and

[1] JOUR. GEOL.: Vol. VI, p. 436, 1898.

groups appear highly specialized and in their permanent form from the first. So-called intermediate forms like Cheirostrobus appear long after the forms they are supposed to connect. Genera and species that vary now have always varied and the limits of variation now and in the past have been the same and definitely prescribed. In short Zeillar believes that the evolution of all groups is a matter almost purely of speculation. Doubtless most scientists will fail to accept Zeiller's views as to evolution, and yet it may be well to put a brake now and then to unlimited speculation; a perusal of Zeiller's final chapter certainly compels one to do that.—H. C. COWLES.

A Topographic Study of the Islands of Southern California. By W. S. TANGIER SMITH. Bulletin of the Department of Geology. University of California, Vol. II, pp. 179–230. 1900.

This bulletin involves an account of certain islands which have been studied in the field, and of others which have been studied from maps only. Following a description of the general topography of the islands, there is a somewhat full discussion of certain coastal features, especially of wave-cut terraces, and of wave and current-built features. This discussion is incisive, and will be of service to the student of coastal topography.

Following the descriptive matter there is a sketch of the history of the islands, from which the following extracts are made:

It is generally assumed that the broad physical features of the Pacific Coast were largely developed during the prolonged period of erosion between the Miocene and Pliocene,[1] and that these forms have been modified more or less by subsequent movements, both general and local, as well as by subsequent erosion and deposition. During the Miocene the land was depressed, as indicated by the Miocene deposits, the nonconformity between these and the Pliocene deposits showing a period of subaerial erosion, during which the land was more elevated than at present. This period of elevation and erosion was followed by the Pliocene depression, during which deposits of great thickness were laid down in favorable localities, the larger Miocene valleys being filled to a greater or less extent with deposits which have since been re-excavated to a greater or less extent.

[1] By the long interval between the Miocene and Pliocene is doubtless meant the long interval between the deposition of the California coastal Miocene, and the Pliocene of the same region.

During the post-Miocene interval, it is probable that all the islands then differentiated were mountainous masses belonging to the mainland. Judging from their topography, and the apparent genetic relationships of those of the northern group, the forms then existing probably included all the present islands, except San Nicolas and San Clemente. The latter appears not to have been elevated till the close of the post-Miocene period, or early in the Pliocene depression, and it is probable that the elevation of San Nicolas occurred at about the same time. The disturbance at this time seems to have been general for this whole region, including both faulting and folding, and leading not only to the differentiation of these two islands, but also, probably, to a greater elevation of all the other islands. Although the forces operative in these movements are believed to have acted intermittently from that time to the present, it is thought that they were mainly effective then; and that any later movements have been of minor importance in relation to the general movements of the California coast, since the highest elevated terraces of San Clemente and the leveled summits of Santa Cataline and Santa Rosa still closely correspond in altitude with the highest terraces on the mainland, and, going farther north, with the upper limit of the Pliocene delta deposits along the Tres Pinos Creek.

The post-Miocene elevation of the coast was followed by the Pliocene depression, during which the sea stood for a long time some 1500 feet below [above ?] its present level as shown by the highest terraces, the planation of the island summits, and the delta deposits just referred to. Whether this was the full extent of this depression for the southern coast cannot be stated from the evidence at present available. During this depression, at first Santa Cataline, San Clemente, San Pedro Hill, Santa Cruz, and Santa Rosa, all probably existed as islands; or, in the case of Santa Cruz and Santa Cataline, as two or more small islands. At this level the ocean remained, cutting away the tops of these islands, till in the case of San Pedro Hill, and perhaps of Santa Rosa also, they were probably wholly truncated, leaving submarine banks like those of the region today. It is possible that San Nicolas was also above sea level at that time, and has since been planed off to its present lower level. Of San Clemente there remained a small nucleus, near the center of the northern half of the island. Santa Cataline was reduced to a small island lying to the north of the center of the present larger division of the island, with probably one or more distant rocks, or smaller islands, toward the present extremities of the island. Santa Cruz, at that time probably existed as a single narrow island, or a line of islands, with a length of at least seven miles, and formed from the northern ridge of the western or main division of the present island. Then, as now, Santa Cruz was probably the highest, if not the largest, of the existing islands.

This depression was followed by a post-Pliocene elevation, as shown both by the present elevation of the Pliocene deposits, and by the elevated coastal

terraces. . . . . The writer is inclined, from present information, to the view of one general elevation of the California coast in post-Pliocene times, accompanied by minor oscillations, and by local differential movements, such as that called for, for example, in the formation of San Francisco Bay. . . . .

It is probable that while the oscillations of post-Pliocene times have been sufficient to connect the northern islands with the mainland, none of the southern islands have had such connection since the post-Miocene period of erosion.

The most recent movement of the coast, as indicated by drowned valleys and submarine features, is a comparatively slight depression, the evidence for which, on the southern California coast, has already been given in detail. The later history of the coast seems, therefore, to be most satisfactorily summed up in a single post-Pliocene elevation, interrupted by minor reverse movements, of which this most recent depression is probably one.

Whether or not future investigation shall lead to modification of the details of the coastal movements as here outlined, is immaterial to the main conclusions of the present paper; the principal point which it aims to establish being the fact that the latest general movements of the islands and coastline of southern California have been the same. R. D. S.

CORRECTION.

In Professor Spurr's article on "Succession and Relation of Lavas in the Great Basin Region," in the last number of the JOURNAL, the caption of the table opposite page 642 should read: "Provisional Correlation of Tertiary Lavas in the Great Basin," not "Great Britain."

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